Published in final edited form as:

IEEE Trans Ultrason Ferroelectr Freq Control. 2013 June ; 60(6): 1272–1276. doi:10.1109/TUFFC.2013.2692.

Lead-Free Intravascular Ultrasound Transducer Using BZT-50BCT Ceramics

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Abstract

This paper reports the fabrication and evaluation of a high-frequency ultrasonic transducer based on a new lead-free piezoelectric material for intravascular imaging application. Lead-free $0.5\text{Ba}(\text{Zr}_{0.2}\text{Ti}_{0.8})\text{O}_3-0.5(\text{Ba}_{0.7}\text{Ca}_{0.3})\text{TiO}_3$ (BZT-50BCT) ceramic with a high dielectric constant (~ 2800) was employed to develop a high-frequency (~ 30 MHz) needle-type ultrasonic transducer. With superior piezoelectric performance (piezoelectric coefficient $d_{33} \sim 600$ pC/N), the lead-free transducer was found to exhibit a -6 -dB bandwidth of 53% with an insertion loss of 18.7 dB. *In vitro* intravascular ultrasound (IVUS) imaging of a human cadaver coronary artery was performed to demonstrate the potential of the lead-free transducer for biomedical imaging applications. This is the first time that a lead-free transducer has been used for IVUS imaging application. The experimental results suggest that the BZT-50BCT ceramic is a promising lead-free piezoelectric material for high-frequency intravascular imaging applications.

I. INTRODUCTION

INTRAVASCULAR ultrasound (IVUS) is a catheter-based imaging technique which has been proven to be a useful clinical tool for the diagnosis and therapy of coronary diseases. IVUS is

capable of imaging the vessel wall so as to allow the physicians to perform an accurate evaluation of lumen dimensions, calcium content, and other plaque characteristics [1], [2]. In recent years, intensive effort has been made in improving IVUS imaging performance by adopting better transducer materials [3], increasing transducer frequency [4], and even combining it with other imaging modalities [5]-[7].

Among these options, proper piezoelectric material selection in ultrasonic transducer design is of utmost importance because the transducer element plays a critical role on the transducer performance. Because of their excellent piezoelectric performance, lead-based piezoelectric materials such as PZT and PMN-PT are often used for intravascular imaging applications [8]-[11]. However, the application of toxic lead-based materials causes serious environmental concerns. Therefore, there is an urgent demand for developing lead-free substitutes for intravascular imaging applications. Currently, great progress on lead-free systems with a perovskite-type structure, such as KNN-based and BNT-based ceramics, have been made [12]-[16]. A shortcoming of lead-free piezoelectric materials is that they exhibit much lower piezoelectric properties than the lead-based families. Recently, Liu *et al.* [17] developed a new lead-free pseudobinary ferroelectric system $(1 - x)\text{Ba}(\text{Zr}_{0.2}\text{Ti}_{0.8})\text{O}_3 - x(\text{Ba}_{0.7}\text{Ca}_{0.3})\text{TiO}_3$ (hereafter abbreviated as BZT-100xBCT). The material demonstrates excellent piezoelectricity with a d_{33} value of 560 to 620 pC/N at BZT-50BCT, which is comparable to PZT. Therefore, it is considered to be a promising piezoelectric material for ultrasonic transducer applications.

In this paper, an IVUS transducer fabricated using the lead-free BZT-50BCT ceramic is reported. Based on the superior performance of the ceramic, a highly sensitive 30.5-MHz lead-free IVUS transducer was developed. The experimental results were compared with those reported for other lead-based transducers. *In vitro* IVUS imaging of a human cadaver coronary artery was performed to demonstrate the potential of its biomedical imaging applications.

II. EXPERIMENTAL PROCEDURE

BZT-50BCT ceramic was prepared with a conventional solid-state reaction method. The starting chemicals are BaZrO_3 (98%), CaCO_3 (99.9%), BaCO_3 (99.95%), and TiO_2 (99.9%). Calcination was performed at 1350°C, and sintering was done at 1450°C in air. A brief list of the material properties for BZT-50BCT ceramic is shown in Table I. The high piezoelectric ($d_{33} = 597$ pC/N) and electromechanical coupling coefficient ($k_t = 0.41$) indicate that the lead-free ceramic is attractive for piezoelectric device applications. The high dielectric constant ($\epsilon^s/\epsilon_0 = 2817$) of BZT-50BCT ceramic makes it more conducive to developing miniature high-frequency transducers and arrays. Nevertheless, its relatively low Curie temperature ($T_c = 93^\circ\text{C}$) may limit its thermal stability during the transducer fabrication process and device operation in medical imaging applications.

A single-element needle transducer was fabricated using conventional transducer technology to evaluate the performance of BZT-50BCT ceramic for high-frequency ultrasonic transducer applications. The dimensions of the acoustic stack, including BZT-50BCT ceramic and dual matching layer, were optimized by a PiezoCAD simulation program

(Sonic Concepts Inc., Bothell, WA). First, the BZT-50BCT ceramic was lapped to 75 μm and the Cr/Au (500 $\text{\AA}$ /1000 $\text{\AA}$) electrodes were sputtered on both surfaces of the ceramic. A matching layer made of Insulcast 501 and Insulcure 9 (American Safety Technologies, Roseland, NJ) and 2- to 3- μm silver particles (Sigma-Aldrich Inc., St. Louis, MO) was cured on one side of the BZT-50BCT ceramic and lapped to 10 μm . A conductive backing material, E-solder 3022 (VonRoll Isola, New Haven, CT), was cured on the opposite side of the BZT-50BCT ceramic and lapped to 1.5 mm. The active acoustic stack, including the first matching layer, the ceramic, and the backing layer, was then diced to 0.8×0.8 mm. The sample was inserted into a polyimide tube (MedSource Technologies, Trenton, GA) in which a 0.1-mm-diameter lead wire was connected to the backing layer using conductive epoxy. Then, the tube was fixed into the housing of a steel needle using epoxy (Epotek 301-2, Epoxy Technology Inc., Billerica, MA). A Cr/Au (500 $\text{\AA}$ /1000 $\text{\AA}$) layer was sputtered across the silver matching layer and the needle housing to form a ground electrode. Parylene with a thickness of 16 μm was evaporated onto the front surface of the transducer to serve as the second matching layer and also a protection layer. A schematic diagram of the transducer is shown in Fig. 1. The transducer was then assembled into a brass housing with an SMA connector for further experiments, as shown in Fig. 2. After fabrication, the transducer was poled in air at 40°C under an electric field of 0.7 kV/mm for 10 min.

III. RESULTS AND DISCUSSION

A. Transducer Characterization

The electrical impedance characteristics of the transducer were measured by an electric impedance analyzer (HP 4294A, Agilent Technologies, Santa Clara, CA). The effective electromechanical coupling coefficient, k_{eff} , describing the conversion of energy between electrical and mechanical, was calculated from [18]:

$$k_{\text{eff}} = \sqrt{1 - \frac{f_s^2}{f_p^2}}, \quad (1)$$

where f_s is the series resonant frequency at which the conductance reaches maximum and f_p is the parallel resonant frequency at which the resistance reaches maximum. As shown in Fig. 3, the f_s and f_p of the transducer are 30.05 and 34.85 MHz, respectively. The k_{eff} was then calculated to be 0.51.

The performance of the transducer was then evaluated in deionized water at room temperature with a pulse–echo arrangement. An X-cut quartz plate was used as a target and the transducer was excited by a pulser/receiver (5900PR, Panametrics NDT, Waltham, MA) with 200 Hz repetition rate and 50 Ω damping. The reflected waveform was received and digitized by a 1-GHz oscilloscope (LC534, LeCroy Corp., Chestnut Ridge, NY) with 50 Ω coupling. The fast Fourier transform (FFT) feature on the oscilloscope was used to display the frequency spectrum of the received waveform. The center frequency (f_c) and –6-dB fractional bandwidth (BW) are determined by [19]

$$f_c = (f_1 + f_u) / 2, \quad (2)$$

$$BW = (f_u - f_l) / f_c \times 100\%, \quad (3)$$

where f_l and f_u are defined as lower and upper -6 -dB frequencies, respectively, at which the magnitude of the amplitude in the spectrum is 50% (-6 -dB) of the maximum. The measured pulse–echo waveform and frequency spectrum of the BCT-50BZT transducer are shown in Fig. 4. The f_l and f_u were found to be 22.4 and 38.5 MHz, respectively. According to (2) and (3), the center frequency of the transducer was about 30.5 MHz, and the bandwidth at -6 dB was close to 53%. Without signal amplification, the output voltage of the transducer was 334 mV.

The two-way insertion loss was measured using a function generator (AFG 2020, Tektronix Inc., Richardson, TX) with 50Ω output impedance. The distance between the transducer and the quartz plate was kept identical to that in the previous pulse–echo measurement. A tone burst of a 30-cycle sine wave with an amplitude of 5 V was generated at the center frequency of the transducer as a signal source. The echo signal was acquired and displayed using the 1-GHz digital oscilloscope with $1 \text{ M}\Omega$ coupling. It was found that the echo signal amplitude was about 450 mV. After the signal loss from the transmission into the quartz target (1.9 dB) and attenuation in water ($2.2 \times 10^{-4} \text{ dB/mm}\cdot\text{MHz}^2$) [20] was compensated, the insertion loss of the transducer was calculated to be -18.7 dB.

B. In Vitro Intravascular Imaging

To evaluate the intravascular ultrasound (IVUS) imaging capability of the lead-free transducer, a 45° polished glass mirror was installed in the front of the transducer to redirect the ultrasonic beam by 90° . The mirror and transducer were properly aligned and housed in a plastic tube in which a window was made to allow the ultrasound beam to be transmitted and received. The transducer was then connected to a stepper motor (National Instruments, Austin, TX) through a brushed electrical slip ring (Prosperous Co. Hangzhou, China) to allow the free rotation of the transducer while transmitting electrical signals between rotational and stationary parts.

In this study, *in vitro* IVUS imaging of a human cadaver coronary artery was performed to evaluate the lead-free transducer performance. In the experiment, the tip of the transducer was positioned inside a lumen of the specimen, which was immersed in saline. The circumferential scanning was achieved by rotating the transducer. A Panametrics 5900PR pulser/receiver was used to drive the transducer for pulse generation and echo detection. RF data was digitized by a 12-bit data acquisition board (Gage Applied Technologies, Lockport, IL) with a sampling rate of 400 MHz. 1000 A-lines were acquired during each revolution and the scanning procedure was controlled by a customized LabVIEW program (National Instruments, Austin, TX). The RF data were saved and post-processed for the image display. The image was displayed with a 50 dB dynamic range.

The image acquired as shown in Fig. 5 shows that the lead-free transducer exhibited satisfactory resolution, penetration, and sensitivity to allow visualization of the thickened intima (fibrous plaque) and even a poor signal region on an inner layer of the vessel. The

brighter region clearly marks the outer border of the fibrous plaque. The IVUS image shows that the transducer had adequate penetration so that it can see through the entire vessel wall.

C. Discussion

A lead-free IVUS transducer has been developed successfully using the BZT-50BCT ceramic. It exhibited reasonable characteristics compared with the PiezoCAD simulation results ($f_c = 30.75$ MHz, -6 -dB bandwidth = 47%), shown in Fig. 6. The experimental results of the BZT-50BCT transducer were also compared with the reported results of other lead-based transducers in literature (shown in Table II). The -6 -dB bandwidth of the BZT-50BCT transducer is slightly higher than those of PMN-33PT and PT transducers. Although the insertion loss of the BZT-50BCT transducer is slightly higher than that of PMN-33PT transducer (15.0 dB), however, it is much lower than that of PT transducer (23.7 dB). With superior piezoelectric performance of the BZT-50BCT ceramic, the performance (sensitivity and bandwidth) of the lead-free BZT-50BCT transducer was demonstrated to be comparable to high-performance lead-based transducers.

For the *in vitro* IVUS imaging of a human cadaver coronary artery, the image acquired from the lead-free BZT-50BCT transducer demonstrated satisfactory resolution and contrast to differentiate the vessel wall and fibrous plaque clearly. The image quality is comparable to other IVUS images reported in literature. Moreover, the transducer active element is an environmentally friendly lead-free material. The study shows that this novel lead-free ceramic has great potential to be extensively used for IVUS and endoscope imaging applications.

IV. CONCLUSIONS

The new lead-free BZT-50BCT ceramic, with high piezoelectric and dielectric characteristics, is suitable for the development of high-performance miniature ultrasonic transducers. A 30.5-MHz IVUS transducer was successfully fabricated using the BZT-50BCT ceramic. The lead-free transducer was found to exhibit a -6 -dB bandwidth of 53% with an insertion loss of 18.7 dB. The performance (sensitivity and bandwidth) of the BZT-50BCT transducer is comparable to high-performance lead-based transducers. The IVUS image acquired from the lead-free transducer shows good imaging capability with high sensitivity and resolution. The present work demonstrates that the BZT-50BCT ceramic is a promising lead-free candidate to replace the lead-based materials for high-frequency ultrasonic transducer applications.

Acknowledgments

This work was financially supported by the International Science and Technology Cooperation Program of China (grant number 2010DFB13640), National Basic Research Program of China (grant number 2012CB619401), Natural Science Foundation of China (grant number 90923001), the Shaanxi Province International Collaboration Program (grant numbers 2009KW-12 and 2010KW-09), and the National Institutes of Health (NIH; grant number P41-EB002182).

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Fig. 1.
Schematic diagram of BZT-50BCT transducer.

Fig. 2.
Photograph of BZT-50BCT transducer.

Fig. 3.
Electrical impedance magnitude and phase of BZT-50BCT transducer.

Fig. 4.
Measured pulse-echo waveform and frequency spectrum of BZT-50BCT transducer.

Fig. 5.
Intravascular ultrasound image acquired from BZT-50BCT transducer.

Fig. 6. Simulated pulse-echo waveform and frequency spectrum of BZT-50BCT transducer.

TABLE I

MATERIAL PROPERTIES OF BZT-50BCT CERAMIC

Property	Value
Electromechanical coupling coefficient k_t	0.41
Piezoelectric constant d_{33} (pC/N)	597
Relative clamped dielectric constant ϵ^s/ϵ_0	2817
$\tan \delta$ at 1 kHz (%)	2.0
Density (kg/m ³)	5200
Longitudinal wave velocity (m/s)	5133
Acoustic impedance (MRayl)	26.7
Curie temperature (°C)	93

TABLE II

SUMMARY OF PERFORMANCE OBTAINED FROM DIFFERENT ULTRASONIC TRANSDUCERS

Material	Center frequency (MHz)	−6 dB Bandwidth (%)	Insertion loss (dB)
BZT-50BCT ceramic	30	53	18.7
PT ceramic [21]	45	47	23.7
PMN-33PT single crystal [22]	44	45	15.0