Published in final edited form as:

Ultrasonics. 2013 July ; 53(5): 1033–1038. doi:10.1016/j.ultras.2013.01.012.

Development of lead-free single-element ultrahigh frequency (170 – 320 MHz) ultrasonic transducers

Kwok Ho Lam^{1,*}, Hong Fen Ji², Fan Zheng¹, Wei Ren², Qifa Zhou¹, and K. Kirk Shung¹

¹Department of Biomedical Engineering and NIH Transducer Resource Center, University of Southern California, Los Angeles, CA 90089-1111, USA

²Electronic Materials Research Laboratory, Key Laboratory of the Ministry of Education & International Center for Dielectric Research, Xi'an Jiantong University, Xi'an, 710049, China

Abstract

This paper presents the design, fabrication and characterization of single-element ultrahigh frequency (UHF) ultrasonic transducers in which the center frequency ranged from 170 to 320 MHz. The center frequency of > 300 MHz is the highest value of lead-free ceramic ultrasonic transducers ever reported. With concern in the environmental pollution of lead-based materials, the transducer elements presented in this work were lead-free $K_{0.5}Na_{0.5}NbO_3/Bi_{0.5}Na_{0.5}TiO_3$ (KNN/BNT) composite thick films. All transducers were evaluated in a pulse-echo arrangement. The measured –6 dB bandwidth of the transducers ranged from 35 to 64 %. With the optimized piezoelectric properties of the composite film, the insertion loss of the UHF transducers was measured and determined to range from –50 to –60 dB. In addition to the pulse-echo measurement, a 6- μ m tungsten wire phantom was also imaged with a 205 MHz transducer to demonstrate the imaging capability. The measured –6 dB axial and lateral resolutions were found to be 12 μ m and 50 μ m, respectively. The transducer performance presented in this work is shown to be better or comparable to previously reported results even though the frequency is much higher.

Keywords

UHF ultrasonic transducer; lead-free; composite sol-gel; thick film

1. Introduction

Ultrasonic imaging is one of the most important medical diagnostic tools used today. Compared to other clinical imaging modalities such as magnetic resonance imaging (MRI), x-ray computed tomography (CT), and nuclear imaging, ultrasound provides images with comparable quality and resolution at low cost without exposing patients to ionizing radiation. With its non-invasive characteristics, the use of ultrasonic imaging is expanding into new clinical applications. High frequency (HF) ultrasound has found many applications in the diagnosis of arterial diseases [1-3], problems in the anterior segment of the eye [4, 5],

© 2013 Elsevier B.V. All rights reserved.

*Fax: +1-213-821-2651, kokokhlam@gmail.com.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

and characterization of skin lesions [6, 7] due to its enhanced spatial resolution. It has also played a significant role in small animal preclinical imaging [8, 9].

In addition to imaging applications, other applications of HF ultrasound have been investigated. As the frequency is increased to beyond 100 MHz, the beam dimension would approach the cellular level. Ultrasound beams at ultrahigh frequencies (UHF), frequencies higher than 100 MHz, have thus been dubbed “ultrasound microbeams”. It has been found that ultrasound microbeam can be used to acoustically trap and sort small particles (in micron size) and cells [10-12]. For such applications, UHF transducers with desirable performance are needed. Traditionally, zinc oxide (ZnO) has been the material for UHF (200 MHz - 1 GHz) transducer design [13] because it has a low dielectric constant ($\epsilon^S \sim 4$) and it can be deposited in very thin layers ($\sim 1 \mu\text{m}$) with excellent uniformity on a substrate. However, due to its low electromechanical coupling coefficient ($d_{33} \sim 10 - 26 \text{ pm/V}$, $k_t \sim 0.28$), other piezoelectric thick/thin films with higher electromechanical coupling coefficients are needed to offer better performance. Because of the high voltage (receiving) coefficient ($d_{33} \sim 33 \text{ pC/N}$, $\epsilon^S = 5$, $g_{33} \sim 280 \times 10^{-3} \text{ V m/N}$), piezoelectric polymer (e.g. polyvinylidene fluoride (PVDF)) or copolymer (e.g. polyvinylidene fluoride-trifluoroethylene (P(VDF)-TrFE)) has also been used for many commercial high frequency (in 100 MHz range) single element transducers [14]. With a low dielectric permittivity ($\epsilon^S \sim 14$), lithium niobate (LN) offers a viable alternative [15].

In the fabrication of ultrahigh frequency transducers, one of the technical challenges is the preparation of the piezoelectric element [16]. Piezoelectric material thickness on the order of only a few microns must be prepared. Among various thick film fabrication methods, a composite sol-gel technique [17] has attracted much interest to develop dense and crack-free ceramic films [18, 19]. For the transducer element material, since the traditional lead-based ceramics ($> 60\%$ lead in PZT by weight) cause environmental pollution by releasing the lead during the fabrication process, the trend is to develop relatively environmental friendly lead-free material systems [20].

Among the lead-free material systems, $(\text{K}_{0.5}\text{Na}_{0.5})\text{NbO}_3$ (KNN)-based and bismuth sodium titanate $(\text{Bi}_{0.5}\text{Na}_{0.5})\text{TiO}_3$ (BNT)-based materials are promising candidates. The KNN-based ceramics have been found to exhibit high piezoelectric ($d_{33} \sim 210 - 270 \text{ pC/N}$) and electromechanical coupling coefficients ($k_t \sim 0.47$) [21, 22] while the BNT-based ceramics shows strong ferroelectricity ($E_c \sim 37 \text{ kV/cm}$; $P_r \sim 38 \mu\text{C/cm}^2$) [23, 24]. Both material systems have extensively been used for various electromechanical applications [25-28]. Combining the merits of two systems, a KNN/BNT thick film synthesized by the composite sol-gel technique has been developed [29]. In an initial attempt, a 193-MHz high-frequency ultrasound transducer fabricated using the KNN/BNT film was reported to exhibit a -6 dB bandwidth of 34% [30]. Although the work on the 193-MHz KNN/BNT film transducer was published, the sensitivity of the transducer was poor because of the inhomogeneous quality of the film. With the weak signal of the previous transducer, no insertion loss (sensitivity) could be measured and reported.

In the present work, with the maturity of the fabrication technique, the film quality can be retained even when the film thickness is $< 5 \mu\text{m}$. This manuscript describes the lead free transducer operating at the frequencies exceeding 300 MHz. It is novel because the $> 300 \text{ MHz}$ is the highest center frequency of lead-free ceramic ultrasonic transducers ever reported. Besides achieving much higher transducer frequency, the insertion loss of the transducers can also be measured and reported. Compared to the previous work, the present work is a breakthrough in both material and transducer points of view.

In this work, results on ultrahigh frequency transducers in a frequency range of 170 – 320 MHz designed and fabricated with thinner KNN/BNT films ($< 5 \mu\text{m}$) are reported. Both -6 dB bandwidth and insertion loss of these transducers were measured. The measured transducer characteristics were shown to be comparable to the simulation. To demonstrate their imaging capability, a $6\text{-}\mu\text{m}$ tungsten wire phantom was imaged with a 205 MHz transducer to determine the axial and lateral resolutions. It was found that the present transducer performance is better or comparable to previously reported results even though the frequency is much higher.

2. Methods

In this section, the transducer material, design and fabrication process are described.

A. Transducer element

KNN/BNT composite films were fabricated using a composite sol-gel technique. Based on the traditional sol-gel method, the technology of composite and vacuum infiltration was utilized. To develop the KNN/BNT composite films, KNN ceramic powders were prepared using a conventional solid-state reaction method and BNT precursor solution was synthesized by a sol-gel process. At the annealing temperature of 750°C , the KNN/BNT films with the KNN powder - BNT solution weight ratio of 0.40 were found to exhibit the optimized structural, dielectric and ferroelectric properties [29]. Thus, the composite films with this designated composition were chosen as the transducer element in this study. To further improve the film density and homogeneity, fine KNN powder was obtained by ball-milling for long time (10 hours) and a vacuum infiltration process with BNT precursor solution was applied after each coating of the composite film.

B. Transducer design and fabrication

KNN/BNT composite film ultrasonic transducers were fabricated using conventional transducer technology. The composite films with thicknesses ranging from $3 - 5 \mu\text{m}$ were used to fabricate the ultrahigh frequency transducers (> 170 MHz). A cross-sectional view of the design is shown in Figure 1. Firstly, a very lossy (an attenuation of 112 dB/mm at 30 MHz [31]) conductive epoxy (E-Solder 3022, Von Roll Isola Inc., New Haven, CT) was applied to the transducer element as the backing layer material by centrifuging it at 1200 g for 15 minutes. After curing at room temperature overnight and lapping the backing layer, the sample was diced into small posts with dimensions of $0.2 \times 0.2 \text{ mm}^2$. The composite film with the support of the backing layer was removed from the silicon substrate without any damage using a wet etching method [32]. The acoustic stack was released after immersing in 20% concentrated KOH solution at 80°C for a few minutes. Afterwards, a 1.5 cm -long lead wire was connected to the backing layer using E-Solder 3022 epoxy. The transducer element was fixed inside a metal housing using epoxy (EPOTEK 301, Epoxy Tech., Billerica, MA). After curing the epoxy, a chrome/gold layer of $\sim 1500 \text{ \AA}$ in total thickness was sputtered across the active element and the housing to serve as a common ground. A parylene layer was then vapor-deposited on the front face of the transducer to serve as an acoustic matching layer as well as a protection layer. The transducer prototype was assembled with an SMA connector for further electrical treatments and measurements to facilitate electrical poling and pulse-echo characterization.

A photo of final transducer prototype is shown in Figure 2. The transducers were poled with an electric field of 210 kV/cm using a high voltage power supply (Bertan Associates, Inc., Syosset, NY) at 115°C for 10 minutes so as to induce the piezoelectric performance of the composite thick film. After poling, the transducer was short-circuit annealed at room temperature for 1 hour.

C. Transducer characterization

The performance of the transducer, including bandwidth, insertion loss and pulse length, was evaluated in deionized water using a conventional pulse-echo response measurement [33]. During the measurement, the transducer was connected to a Panametrics (Waltham, MA) model 5910PR pulser/receiver and excited by an electrical impulse. Since the cable length effect on signal loss becomes significant when the transducer frequency is higher than 20 MHz [34], a short cable length (~ 8 cm long) was used to connect the transducer during the measurement. An X-cut quartz plate was used as a target. The testing distance (D) was determined by the following equation:

$$D = \frac{d^2}{4\lambda} \quad (\text{Eq. 1})$$

where d is the aperture size of the transducer and λ is the wavelength in water at the center frequency.

The reflected waveform was received and digitized by a 500-MHz LC534 LeCroy (Chestnut Ridge, NY) oscilloscope with 50 Ω coupling. The built-in math feature of the oscilloscope was used to perform the fast Fourier transform (FFT) of the received waveform. As the pulse-echo response is a two-way measurement, the center frequency (f_c) and the -6 dB bandwidth (BW) were determined from the measured frequency spectrum:

$$f_c = \frac{f_1 + f_2}{2} \quad (\text{Eq. 2})$$

$$BW = \frac{f_2 - f_1}{f_c} \times 100\% \quad (\text{Eq. 3})$$

where f_1 and f_2 represent the lower and upper -6 dB frequencies, respectively.

To measure the insertion loss, a Sony/Tektronix (Beaverton, OR) model AFG2020 function generator with an output impedance of 50 Ω was used to generate a tone burst of a sine wave at the center frequency of the transducer, as measured by an oscilloscope in 1M Ω coupling mode. By connecting the transducer to the function generator, the received echo voltage amplitude was measured using the oscilloscope in 50 Ω coupling mode. To compensate ultrasound transmission into the quartz crystal, 18 % receive pressure/voltage lost was taken into account in the final insertion loss calculation. The signal loss due to attenuation in the water bath was also compensated using an attenuation of 2.2×10^{-4} dB/mm-MHz² [35].

The pulse length (PL) was determined from the time duration when the pulse takes the oscillation at -20 dB (10 %) of its maximum peak amplitude.

To assess the axial and lateral resolutions of the transducer, a cross-sectional image of a wire phantom was acquired using the pulse-echo setup as described above. The phantom consisted of a few diagonally arranged 6 μ m-diameter tungsten wires (California Fine Wire Co., Grover Beach, CA) which were separated by 0.65 mm and 1.5 mm in the lateral and axial distance, respectively. Piezoelectric actuators (Inchworm, Burleigh Inc., Fishers, NY) were used to scan the wires across the transducer sound field with a step size of 2 μ m. The amplified RF waveforms were acquired at each step by the LC534 and then used to form an image offline. The -6 dB resolutions of the transducer were then determined from the axial and lateral line spread functions for the recorded wire image.

3. Results and Discussions

Five composite film transducers were fabricated at ultrahigh center frequencies in the 170 – 320 MHz range. The receive-echo response and frequency spectra of the transducers are shown in Figure 3. It was found that the –6 dB bandwidths ranged from 35 to 64 %. The bandwidth discrepancy is mainly due to the film fabrication method and homogeneity. Although the film performance can be enhanced by infiltrating the ceramic powder into the film, the powder would make the film surface rough so as to affect the thickness (frequency) of the film as well as the film performance. Besides, the homogeneity of the film may also be an issue. As the transducer element was picked from different locations of the film, the performance varied. In this study, the highest center frequency of the transducer was 324 MHz as shown in Figure 3e, which is also the highest value of the lead-free ceramic ultrasonic transducer ever reported. The f_1 and f_2 of the transducer were found to be 267 MHz and 380 MHz, respectively. At the center frequency of 324 MHz, the –6 dB fractional bandwidth was determined to be 35 %. Figure 4 shows the modeled result of this ultrahigh frequency transducer, which was performed by Krimholtz, Leedom and Matthaei (KLM)-model-based simulation software PIEZOCAD (Sonic Concepts, Woodinville, WA). The modeled results show that the modeled center frequency and –6 dB bandwidth are 319 MHz and 38 %, respectively. The comparison shows that the measured data are in agreement with the modeled results. Compared to the modeled data, the experimental transducer frequency and bandwidth are in error by 1.6 % and 7.9 %, respectively.

Table 1 shows the measured performance of the composite transducers. Compared to the previous study [30], the transducer performance has been improved. With thinner composite films, the center frequency range of the transducers has been increased. In addition, the bandwidth remains to be 35 % even as the transducer frequency is increased up to 320 MHz. Since the signal of the UHF transducers is weak and the performance is affected by measurement conditions (such as cable length, high-frequency attenuation of the equipment, etc.), there has been no reported value of the insertion loss for such ultrahigh frequency transducers. In this study, the insertion loss of the transducers could be measured and determined to range from –50 dB to –60 dB. As the transducer element was lead-free thick film and the transducer frequency was ultrahigh, these values of the insertion loss reported in this study are reasonably good when comparing to low-frequency (< 50 MHz) bulk ceramic transducers [36, 37] and a high-frequency (160 MHz) PZT transducer [38] in the literature. The pulse length of the transducers was found to be less than 20 ns.

A 6- μ m wire phantom imaged by the 205-MHz transducer is shown in Figure 5. From the point spread function of the targeted image, the measured –6 dB axial and lateral resolutions were found to be 12 μ m and 50 μ m, respectively. Compared to the theoretical values calculated from the following equations [39]:

$$\text{Axial resolution} \quad R_{ax} = \frac{1}{2} \frac{c}{BW} \quad (\text{Eq. 4})$$

$$\text{Lateral resolution} \quad R_{lat} = \lambda \frac{D}{d} \quad (\text{Eq. 5})$$

where c is the speed of sound in degassed water (~ 1480 m/s). With a fractional bandwidth of 51 %, the theoretical axial and lateral resolutions for the 205-MHz transducer were around 7 μ m and 50 μ m, respectively. It is shown that the measured lateral resolution is identical to the theoretical value, and the measured axial resolution has a percentage error of 71 % compared to the theoretical values.

4. Conclusions

Lead-free KNN/BNT ultrahigh frequency transducers ranging from 170 - 320 MHz have been developed. The transducers were found to exhibit adequate bandwidth and insertion loss for imaging applications. The measured transducer characteristics were shown to be comparable to the theoretical ones. The results imply that the lead-free KNN/BNT composite film can be a promising material for ultrahigh frequency ultrasonic transducer applications.

Acknowledgments

This work was financially supported by NIH Grant P41-EB2182.

References

- [1]. Tobis JM, Mallery J, Mahon D, Lehmann K, Zalesky P, Griffith J, Gessert J, Moriuchi M, Mcrae M, Dwyer ML, Greep N, Henry WL. Intravascular ultrasound imaging of human coronary-arteries invivo – analysis of tissue characterizations with comparison to invitro histological specimens. *Circulation*. 1991; 83:913–926. [PubMed: 1999040]
- [2]. Mudra H, Klauss V, Blasini R, Kroetz M, Rieber J, Regar E, Theisen K. Ultrasound guidance of plasma-schatz intercoronary stenting with a combined intravascular ultrasound balloon catheter. *Circulation*. 1994; 90:1252–1261. [PubMed: 8087934]
- [3]. Leber AW, Becker A, Knez A, Ziegler FV, Sirol M, Nikolaou K, Ohnesorge B, Fayad ZA, Becker CR, Reiser M, Steinbeck G, Boekstegers P. Accuracy of 64-slice computed tomography to classify and quantify plaque volumes in the proximal coronary system - A comparative study using intravascular ultrasound. *J. Am. Coll. Cardiol*. 2006; 47:672–677. [PubMed: 16458154]
- [4]. Coleman DJ, Silverman RJ, Chabi A, Rondeau MJ, Shung KK, Cannata J, Lincoff H. High-resolution ultrasonic imaging of the posterior segment. *Am. J. Ophthalmol*. 1992; 113:381–389. [PubMed: 1558111]
- [5]. Pavlin CJ, Harasiewicz K, Foster FS, Coleman DJ, Silverman RJ, Chabi A, Rondeau MJ, Shung KK, Cannata J, Lincoff H. Ultrasound biomicroscopy of anterior segment structures in normal and glaucomatous eyes. *Ophthalmology*. 2004; 111:1344–1351. [PubMed: 15234135]
- [6]. Turnbull DH, Starkoski BG, Harasiewicz KA, Semple JL, From L, Gupta AK, Sauder DN, Foster FS. A 40-100 MHz B-scan ultrasound backscatter microscope for skin imaging. *Ultrasound Med. Biol*. 1995; 21:79–88. [PubMed: 7754581]
- [7]. Rallan D, Harland CC. Ultrasound in dermatology - basic principles and applications. *Clin. Exp. Dermatol*. 2003; 28:632–638. [PubMed: 14616832]
- [8]. Laschke MW, Koerbel C, Rudzitis-Auth J, Gashaw I, Reinhardt M, Hauff P, Zollner TM, Menger MD. High-resolution ultrasound imaging a novel technique for the noninvasive in vivo analysis of endometriotic lesion and cyst formation in small animal models. *Am. J. Pathol*. 2010; 176:585–593. [PubMed: 20042678]
- [9]. Kagadis GC, Loudos G, Katsanos K, Langer SG, Nikiforidis GC. In vivo small animal imaging: current status and future prospects. *Med. Phys*. 2010; 37:6421–6442. [PubMed: 21302799]
- [10]. Lee J, Ha K, Shung KK. A theoretical study of the feasibility of acoustical tweezers: Ray acoustics approach. *J. Acoust. Soc. Am*. 2005; 117:3273–3280. [PubMed: 15957793]
- [11]. Lee J, Lee C, Kim HH, Jakob A, Lemor R, Teh SY, Lee A, Shung KK. Targeted cell immobilization by ultrasound microbeam. *Biotechnol. Bioeng*. 2011; 108:1643–1650. [PubMed: 21328319]
- [12]. Choe Y, Kim JW, Shung KK, Kim ES. Microparticle trapping in an ultrasonic Bessel beam. *Appl. Phys. Lett*. 2011; 99:233704. [PubMed: 22247566]
- [13]. Jakob A, Bender M, Knoll T, Lemor R, Bender M, Lehnert T, Koch M, Veith M, Zhou Q, Zhu BP, Han JX, Shung KK. Comparison of different piezoelectric materials for GHz acoustic microscopy transducers. *Proc. IEEE Inter. Ultrason. Symp*. 2009:1722–1725.

- [14]. Sherar MD, Foster FS. The design and fabrication of high frequency poly(vinylidene fluoride) transducers. *Ultrason. Imaging*. 1989; 11:75–94. [PubMed: 2734975]
- [15]. Shung KK, Cannata JM, Zhou QF. Piezoelectric materials for high frequency medical imaging applications: a review. *J. Electroceram*. 2007; 19:141–147.
- [16]. Zhou Q, Lau S, Wu D, Shung KK. Piezoelectric Films for High Frequency Ultrasonic Transducers in Biomedical Applications. *Prog. Mater. Sci*. 2011; 56:139–174. [PubMed: 21720451]
- [17]. Barrow DA, Petroff TE, Sayer M. Thick ceramic coatings using a sol gel based ceramic-ceramic 0-3 composite. *Surf. Coat. Tech*. 1995; 76:113–118.
- [18]. Corker DL, Zhang Q, Whatmore RW, Perrin C. PZT ‘composite’ ferroelectric thick films. *J. Eur. Ceram. Soc*. 2002; 22:383–390.
- [19]. Wu DW, Zhou QF, Shung KK, Bharadwaja SN, Zhang DS, Zheng HX. Dielectric and piezoelectric properties of PZT composite thick films with variable solution to powder ratios. *J. Am. Ceram. Soc*. 2009; 96:1276–1279. [PubMed: 20376196]
- [20]. Shrout TR, Zhang SJ. Lead-free piezoelectric ceramics: Alternatives for PZT? *J. Electroceram*. 2007; 19:111–124.
- [21]. Lin DM, Kwok KW, Lam KH, Chan HLW. Structure and electrical properties of $K_{0.5}Na_{0.5}NbO_3$ - $LiSbO_3$ lead-free piezoelectric ceramics. *J. Appl. Phys*. 2007; 101:047111.
- [22]. Lin DM, Kwok KW, Lam KH, Chan HLW. Phase structure and electrical properties of $K_{0.5}Na_{0.5}(Nb_{0.94}Sb_{0.06})O_3$ - $LiTaO_3$ lead-free piezoelectric ceramics. *J. Phys. D – Appl. Phys*. 2008; 41:052002.
- [23]. Takenaka T, Maruyama K, Sakata K. $(Bi_{0.5}Na_{0.5})TiO_3$ - $BaTiO_3$ system for lead-free piezoelectric ceramics. *Jpn. J. Appl. Phys. Part 1*. 1991; 30:2236–2239.
- [24]. Wang XX, Chan HLW, Choy CL. Piezoelectric and dielectric properties of CeO_2 -added $(Bi_{0.5}Na_{0.5})_{0.94}Ba_{0.06}TiO_3$ lead-free ceramics. *Solid State Commun*. 2003; 125:395–399.
- [25]. Lam KH, Wang XX, Chan HLW. Lead-free piezoceramic cymbal actuator. *Sens. Actuator A-Phys*. 2006; 125:393–397.
- [26]. Guo MS, Lin DM, Lam KH, Wang S, Chan HLW, Zhao XZ. A lead-free piezoelectric transformer in radial vibration modes. *Rev. Sci. Instrum*. 2007; 78:035102. [PubMed: 17411212]
- [27]. Lam KH, Lin DM, Chan HLW. Lead-free acoustic emission sensors. *Rev. Sci. Instrum*. 2007; 78:115109. [PubMed: 18052506]
- [28]. Lam KH, Lin DM, Kwok KW, Chan HLW. Lead-free Piezoelectric-Metal-Cavity (PMC) Actuators. *IEEE Trans. Ultrason., Ferroelect., Freq. Contr*. 2008; 55:1682–1685.
- [29]. Ji H, Ren W, Wang L, Shi P, Chen X, Wu X, Yao X, Lau ST, Zhou Q, Shung KK. Enhanced structures and electrical properties of lead-free $K_{0.5}Na_{0.5}NbO_3$ - $Bi_{0.5}Na_{0.5}TiO_3$ 0-3 composite ferroelectric thick films. *IEEE Trans. Ultrason., Ferroelect., Freq. Contr*. 2011; 94:3425–3430.
- [30]. Lau ST, Ji HF, Li X, Ren W, Zhou Q, Shung KK. KNN/BNT composite lead-free films for high-frequency ultrasonic transducer applications. *IEEE Trans. Ultrason., Ferroelect., Freq. Contr*. 2011; 58:249–254.
- [31]. Ritter T, Shung KK, Geng X, Lopath P, Tutwiler R, Shrout T. Composite ultrasound transducer arrays for operation above 20 MHz. *Proc. SPIE*. 1999; 3664:67–75.
- [32]. Zhu B, Han J, Shi J, Shung KK, Wei Q, Huang Y, Kosec M, Zhou Q. Lift-off PMN-PT thick film for high-frequency ultrasonic biomicroscopy. *J. Am. Ceram. Soc*. 2010; 93:2929–2931. [PubMed: 21170158]
- [33]. Cannata JM, Ritter TA, Chen WH, Silverman RH, Shung KK. Design of efficient, broadband single-element (20-80 MHz) ultrasonic transducers for medical imaging applications. *IEEE Trans. Ultrason., Ferroelect., Freq. Contr*. 2003; 50:1548–1557.
- [34]. Chen WH, Cao PJ, Maione E, Ritter T, Shung KK. Optimization of pulse transmission in a high-frequency ultrasound imaging system. *Proc. IEEE Inter. Ultrason. Symp*. 2001:995–998.
- [35]. Lockwood GR, Turnbull DH, Foster FS. Fabrication of high frequency spherically shaped ceramic transducers. *IEEE Trans. Ultrason., Ferroelect., Freq. Contr*. 1994; 41:231–235.

- [36]. Snook KA, Zhao JZ, Alves CHF, Cannata JM, Chen WH, Meyer RJ, Ritter TA, Kirk Shung K. Design, fabrication, and evaluation of high frequency, single-element transducers incorporating different materials. *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.* 2002; 49:169–176.
- [37]. Lee STF, Lam KH, Zhang XM, Chan HLW. High frequency ultrasonic transducer based on lead-free BSZT piezoceramics. *Ultrasonics*. 2011; 51:811–814. [PubMed: 21477833]
- [38]. Lukacs M, Sayer M, Foster S. Single element high frequency (> 50 MHz) PZT sol gel composite ultrasound transducers. *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.* 2000; 47:148–159.
- [39]. Foster FS, Pavlin CJ, Harasiewicz KA, Christopher DA, Turnbull DH. Advances in ultrasound biomicroscopy. *Ultrasound Med. Biol.* 2000; 26:1–27. [PubMed: 10687788]

Highlights

- We fabricate lead-free KNN/BNT single-element UHF ultrasonic transducers.
- We develop transducers with an ultrahigh frequency range of 170 – 320 MHz.
- 324 MHz is the highest center frequency of ceramic transducers ever reported.
- UHF transducers exhibit adequate bandwidth and insertion loss.
- Measured transducer characteristics are comparable to the theoretical ones.

Figure 1.
Schematic diagram of the transducer.

Figure 2.
Photograph of the final transducer prototype.

Figure 3. Time-domain pulse/echo response and frequency spectrum for the (a) 171-MHz, (b) 205-MHz, (c) 224-MHz, (d) 278-MHz, and (e) 324-MHz ultrasonic transducers.

Figure 4.
Modeled result of the 320-MHz composite transducer.

Figure 5.
A wire phantom acquired by a 205-MHz plane ultrasonic transducer.

Table 1

Measured performance of ultrahigh frequency transducers.

f_c (MHz)	BW (%)	IL (dB)	PL (ns)
171	47	−50	18
205	57	−58	10
224	42	−55	16
278	64	−56	11
324	35	−60	15