Hard-Type Piezoelectric Materials Based Double-Parabolic-Reflectors Ultrasonic Transducer (DPLUS) for High-Power Ultrasound

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ABSTRACT To achieve wide-frequency (20 kHz-2 MHz) high-power output (10 MPa) of Double Parabolic refLectors wave-guided Ultrasonic tranSducers (DPLUS), this paper investigated the DPLUS with hard-type PZTs. Under resonant excitation of the DPLUS waveguide, around 30 harmonic longitudinal modes from the thin waveguide (1 mm in diameter and 40 mm long) can be excited between 20 kHz to 2 MHz. From 20 kHz to 0.4 MHz, the maximum peak vibration velocity was 7.5 m/s; from 1 MHz to 2 MHz, the maximum peak vibration velocity of hard-type PZT DPLUS (7 m/s) was 3.5 times of soft-type piezoelectric materials DPLUS (2 m/s). Acoustic evaluation revealed large acoustic pressure at a wide frequency range: 0.46 MPa (at 31 kHz), 10 MPa (at 590 kHz), 7.7 MPa (at 1.154 MHz), and 7.2 MPa (at 1.322 MHz). Results proved wide-frequency and high-power operation of DPLUS, which are significant for realizing various applications.

INDEX TERMS High-power ultrasound, DPLUS, harmonic modes, acoustic pressure.

I. INTRODUCTION

High intensity focused ultrasound (HIFU) transducers and Bolt-clamped Langevin transducers (BLT) are two kinds of typical high-power ultrasonic transducers. HIFU transducers are usually used in the frequency range of 0.75 to 3 MHz (high frequency) while BLTs are targeted for 20 to 100 kHz (low frequency). HIFU is widely used for therapeutic ultrasound applications [1], [2], inducing thermal and mechanical effects to the tissue. Mechanical effects involve the acoustic cavitation produced under the high-intensity ultrasound. BLTs are widely used in cavitation-related engineering applications [3] such as ultrasonic cleaning, cavitation-assisted chemical reaction. HIFU transducers can generate high-intensity ultrasound using the acoustic focusing reflectors. The focusing gain can be over 100 times, and the focused peak positive acoustic pressure can be over 100 MPa [1]. Such high acoustic output is determined by the design parameters

such as wavelength, aperture diameter, and F number. When the working frequency is changed, a HIFU transducer with a different design is used, therefore, one HIFU transducer is designed only for one or two working frequencies. BLTs are superior for low-frequency high-power ultrasound. The total length of BLTs is usually half wavelength in order for having a high mechanical quality factor. When the working frequency is increased to such as a few megahertz, the wavelength becomes too small, and the extreme aspect ratio makes it difficult to design BLTs. Again, one BLT is designed for one or two working frequencies. For applications that the optimal working frequency is known, one HIFU transducer or one BLT working at the optimal frequency would be good enough. However, when the frequency dependence is unknown, a new type of ultrasonic transducer is required to examine the frequency dependence, which requires a wide working frequency range and high-power output. After characterizing the frequency dependence by such transducers, HIFU transducers or BLTs can be designed accordingly.

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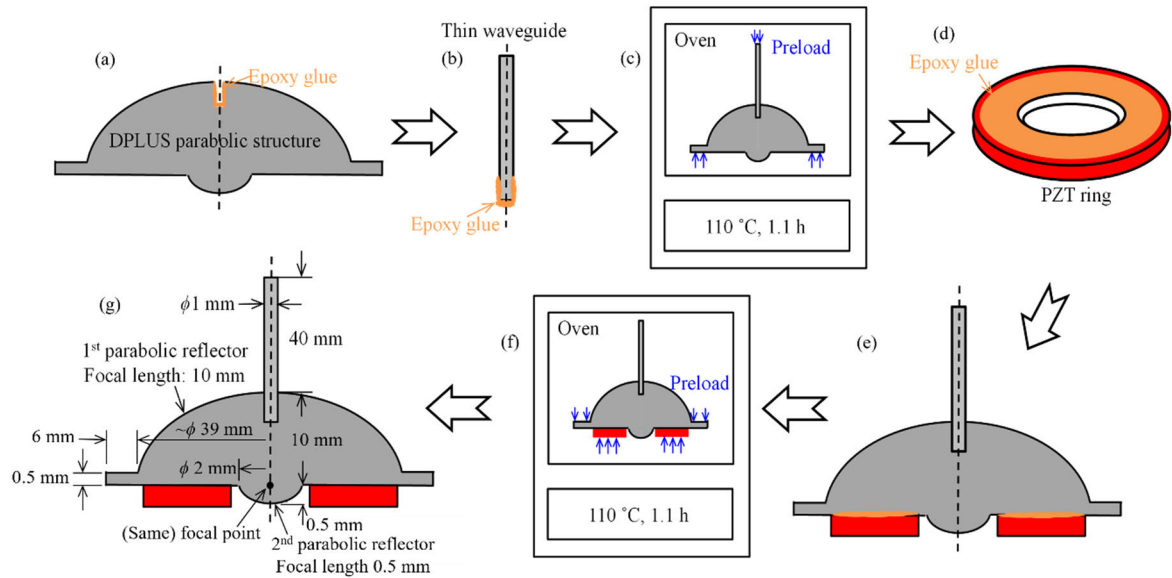
FIGURE 1. Assembling process of DPLUS. (a) The DPLUS parabolic structure and (b) the thin waveguide were covered with the epoxy glue. (c) The curing process was conducted in an oven with 110 °C for 1.1 hours. (d) The PZT ring was covered with the same epoxy glue. (e) The PZT ring was glued to the DPLUS parabolic structure and (f) the curing process was conducted in an oven with 110 °C for 1.1 hours. (g) Illustration of the assembled DPLUS. Same focal point means two parabolic reflectors share the same focal point.

To provide further insights of designing such an ultrasonic transducer that can achieve wide working frequency and high-power output, we looked deeper into acoustic cavitation. In the field of high-power ultrasonics, acoustic cavitation is a powerful tool for realizing various biomedical applications [1]–[3]. Studies showed that dual- or multiple-frequency excitation can extensively enhance the cavitation effect. P. Ciuti *et al.* revealed that the short-time action of a low-frequency ultrasound (27.2 kHz) in a high-frequency (730 kHz) pulsed field remarkably lowed the cavitation threshold and increased the sonoluminescence intensity [4]. Barati *et al.* studied the combination of low-frequency (150 kHz) and high-frequency (1 MHz) ultrasound for sonodynamic therapy application, and they found that the activity of cavitation produced by the combined field was remarkably higher than the algebraic sum of effects produced by fields separately [5]. Liu and Hsieh designed one ultrasonic transducer that can operate at three frequencies (83, 241, 271 kHz), and they found that the cavitation bubbles generated by the dual-frequency field can be five times higher than that of the single-frequency field [6]. They suggested such enhancement was because the acoustic field by dual- or multiple- frequency sonication includes a set of frequencies with a much wider range than the sum of single-frequency fields, and thus the bubble sizes vary and the total bubble number increases. Yasuda *et al.* suggested a first- and second-harmonic frequency (0.8 MHz and 1.6 MHz) exposure for enhancing the cavitation bubble for HIFU treatment [7]. In these literatures, there are two points to be emphasized: on the one hand, the selection of frequencies was not consistent, i.e., the optimal frequency combination has not been revealed;

on the other hand, no single transducer can operate at wide working frequencies (20 kHz to 2 MHz), therefore, multiple transducers had to be used. In summary, it deserves our efforts to design and study a new type of transducer that can solve these problems.

Double Parabolic refLectors wave-guided Ultrasonic tranSducer (DPLUS) is one candidate proposed by the current authors [8], [9]. The basic idea to use DPLUS is to propagate the incident wave through two parabolic reflectors as illustrated in Fig. 1(g), as a result, plane-wave ultrasound with high energy density is propagated to the thin waveguide [9]. The plane-wave ultrasound is important for properly exciting the propagation modes in the thin waveguide. When DPLUS works at resonance, over 20 odd-number harmonic longitudinal modes (20 kHz to 2.5 MHz) from the thin waveguide can be excited with large vibration velocities (maximum of 7.5 m/s) [10]. In the case of a 40 mm long thin waveguide which is used in this study, these harmonic resonant frequencies should be $n \times f_1$, where f_1 equals 31 kHz and n is an odd integer. Due to such unique features, DPLUS had been studied for multi-functional acoustic tweezers and minimally invasive therapeutic applicators [11], [12]. Our previous investigation on the selection of piezoelectric materials for DPLUS showed that soft-type piezoelectric materials based DPLUS cannot realize high-frequency (1-2 MHz) and high-power operation (10 MPa) [13]. The maximum peak vibration velocity in the DPLUS thin waveguide was less than 2 m/s, which is less than approximately 4 MPa of acoustic pressure in water. Therefore, it is required to improve the mechanical and acoustic output of DPLUS. In this paper, we introduce hard-type PZT

(lead zirconate titanate) to DPLUS for realizing high-power output.

II. MATERIALS AND METHODS

Two hard-type lead zirconate titanate (PZT) piezoelectric materials were prepared: PZT 18K and PZT 831. They were provided by NGK Spark Plug Co., Ltd. PZT 18K has a catalogue mechanical quality factor (Q_m) of 1800 and that of PZT 831 is 1200. Material properties were summarized in Table 1. Four soft types were also given, which had been studied in our previous paper [13]. These materials were made into ring shapes. The polarization directions were aligned in the thickness direction, and the electrodes were covered on the top and bottom surfaces of the rings. Before assembling into a DPLUS, admittance and vibration characteristics of the piezoelectric rings were examined to determine the thickness mode resonant frequencies f_s. By experiments, f_s is 1.571 MHz and 1.598 MHz for PZT 18K and PZT 831, respectively. Then, the piezoelectric rings and DPLUS metal waveguides were assembled based on the process shown in Fig. 1. The DPLUS metal waveguide including a parabolic structure and a thin waveguide was made of Duralumin A2017, which has high strength, large mechanical quality factor, and good machinability. In each DPLUS metal waveguide, the focal lengths of the 1st and 2nd parabolic reflectors were designed as 10 mm and 0.5 mm; the thin waveguide was 1 mm in diameter and 40 mm in length.

The assembling process is described as follows. First, a thin waveguide was glued to a metal parabolic structure using a heat resistant epoxy (EpiFine) as shown in Figs. 1(a)-1(b). The curing process was conducted in a heating oven with 110 °C for 1.1 hours as shown in Fig. 1(c); a preload force was given to press the thin waveguide to the parabolic structure. Then, a PZT ring was glued to the metal parabolic structure using the same epoxy and heating setup as shown in Figs. 1(d)-1(f). A preload force was given again to ensure the electrically short connection between the electrode surface of the PZT ring and the metal waveguide. Two hard-type PZTs based DPLUS were assembled; soft types were examined in the reference [13]. An illustration of the assembled DPLUS is shown in Fig. 1(g). The size of the DPLUS parabolic structure does not influence the studied resonant frequencies because the target resonant frequencies are from the odd-number harmonic longitudinal modes of the thin waveguide. In the case of a 40 mm long thin waveguide as shown in Fig. 1(g), these harmonic resonant frequencies should be $n \times f_1$, where f_1 equals 31 kHz and n is an odd integer. However, the vibration velocity in the thin waveguide can be influenced by the size of the DPLUS parabolic structure since the stress in the thin waveguide can be changed. This introduces a different research topic for optimizing the DPLUS parabolic structure, which is not the focus of this paper.

In the following, the vibration characteristics of DPLUS using hard-type piezoelectric materials will be revealed, and the analysis for resonant excitation of the DPLUS waveguide is focused. To have a better understanding of the DPLUS,

TABLE 1. Material properties of the piezoelectric rings.

Material	e_{33} (C/m²)	Q_m	$\varepsilon_{33}^T/\varepsilon_0$	f_s (MHz) Simu.	f_s (MHz) Meas.	Z (MRayl)	Dimension (mm³)
PZT 18K	17.9	1800	1450	1.587	1.571	31.56	$\phi40 \times \phi18 \times 1.3$
PZT 831	12.6	1200	1100	1.535	1.598	30.65	$\phi40 \times \phi18 \times 1.3$
PZT 5H	20.91	61	3400	1.783	1.731	33.29	$\phi40 \times \phi18 \times 1.1$
PZT 501	15.81	75	1800	1.891	1.786	35.53	$\phi40 \times \phi18 \times 1.1$
LFP 0202	11.72	51	1400	1.515	1.509	27.42	$\phi40 \times \phi18 \times 2.0$
TR 04	16.11	51	2200	1.202	1.275	24.78	$\phi40 \times \phi18 \times 2.1$

e_{33} is the piezoelectric constant, Q_m is the mechanical quality factor, $\varepsilon_{33}^T/\varepsilon_0$ is the relative dielectric constant, f_s is the fundamental series resonant frequency of the piezoelectric ring at a free-free boundary condition, Z is the specific acoustic impedance of the piezoelectric material. Dimension is expressed as outer diameter×inner diameter×thickness.

TABLE 2. f_{thk} and the vibration velocity at f_{thk} under 5-cycles short burst excitation.

Material	Simulation f_{thk} (MHz)	Simulation Velocity (m/s)	Experiment f_{thk} (MHz)	Experiment Velocity (m/s)
PZT 18K	1.51	0.161	1.46	0.077
PZT 831	1.42	0.116	1.52	0.080

evaluation for non-resonant excitation of the DPLUS waveguide is also introduced.

III. RESULTS AND DISCUSSION

A. NON-RESONANT EXCITATION OF DPLUS WAVEGUIDE

When the excitation cycle to the PZT is short, a standing wave in the DPLUS waveguide cannot be generated, therefore DPLUS waveguide works at non resonance. To excite the propagating wave with a large vibration amplitude, PZT should be excited at the thickness mode resonant frequency and the incident wave to the waveguide should be guided by two parabolic reflections.

As revealed in our previous study [13], the transmitted vibration velocity v_s from the PZT to the metal waveguide at the thickness mode resonant frequency of the PZT is determined by the following equation:

$$v_s = \frac{e_{33}}{d_t} \frac{2V}{Z_m} \quad (1)$$

where e_{33} is the piezoelectric constant, d_t is the thickness of the piezoelectric element, Z_m is the characteristic specific acoustic impedance of the metal waveguide, V is the amplitude of the applied voltage.

The relationship between v_s and the vibration velocity at the thin waveguide tip will be established based on the results from DPLUS with hard-type and soft-type PZTs. For DPLUS with hard-type PZTs, measurements were conducted under 2 and 5 burst cycles excitation (at 10 V_{p-p}), and the vibration velocity at the center of the thin waveguide tip was measured. The thin waveguide tip vibration velocity was plotted in Figs. 2(b)-2(c). Simulation was conducted by PZFlex (Weildlinger Associates, Los Altos, CA, USA),
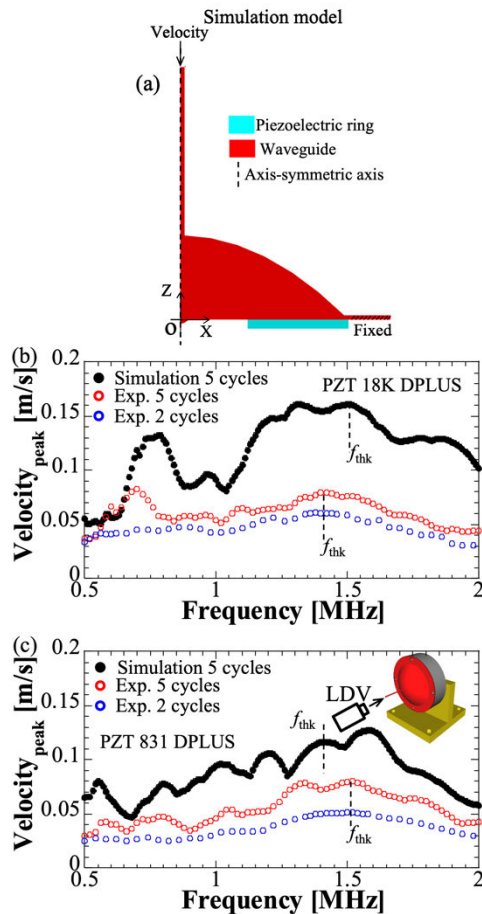
FIGURE 2. Vibration velocity at the thin waveguide tip under short burst excitation. (a) Simulation model. Vibration velocity by simulation and experiments for the (b) PZT 18K DPLUS and (c) PZT 831 DPLUS. The vibration velocity was measured in air.
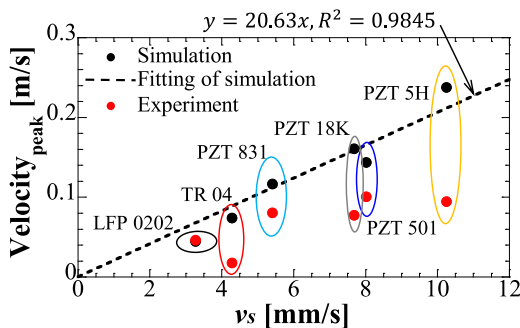

FIGURE 3. Plot of the vibration velocity at f_{thk} against calculated v_s.

with the model shown in Fig. 2(a). An axis-symmetric model was built for improving the calculation efficiency, and the dimension is already illustrated in Fig. 1(g). Lossless metal waveguide was simulated. The simulation frequency range was between 0.5 to 2 MHz with the interval of 0.02 MHz; for each excitation frequency, 5 burst cycles were given to the piezoelectric materials, and the transient response of DPLUS was simulated. In simulation, the PZT surface vibration

velocity was averaged along the width direction, and the peak velocity frequency was used as the thickness mode resonant frequency (f_{thk}) of the PZTs in DPLUS [13], which was indicated in Figs. 2(b)-2(c). From the experimental results under 2 burst cycles, the peak vibration velocity frequency was used as f_{thk}. The values of f_{thk} and the vibration velocity at f_{thk} under 5-cycles burst excitation are shown in Table 2.

For calculating v_s, e_{33} and thickness d_t were taken from Table 1, V and Z_m are 5 volts and 17.9 MRayls, respectively. Plot of the vibration velocity at f_{thk} against the calculated v_s is shown in Fig. 3. Results for the soft-type piezoelectric materials are from the reference [13]. Comparing the simulation and experimental results, certain discrepancy can be observed. The reasons are explained as follows. First, the largest difference occurred for the PZT 5H and TR 04 type DPLUS. It was found because of the gluing layer between the parabolic structure and the piezoelectric ring. Thick gluing layer can be considered as a condenser between the metal waveguide and the piezoelectric ring, which reduces the vibration amplitude of the generated ultrasound by the piezoelectric ring under the same applied voltage. Second, for the LFP 0202, PZT 831, PZT 18K, and PZT 501 type DPLUS, the differences might come from the damping of the waveguide material and the gluing layer between the thin waveguide and the parabolic structure. In the simulation, the material damping was not given to the waveguide and the gluing layer was not modelled. The effects from the waveguide material damping and gluing layer damping are mixed in the experiments. Since the simulation results neglected these damping effects, a linear fitting was given to the simulation results. The goodness-of-fit measure R^2 is 0.9845. The slope of the fitting line can be interpreted as the vibration velocity amplification by double parabolic reflections, which is around 10 times for the current design. From the fitting results, Eq. (1) is proved to be effective for evaluating the piezoelectric materials for DPLUS. Hard-type PZTs do not hold advantages under non-resonant excitation of the DPLUS waveguide.

B. RESONANT EXCITATION OF DPLUS WAVEGUIDE

Multiple modes can be excited for DPLUS working at resonance, which is considered as a good candidate for examining the frequency dependence of various high-power ultrasound applications. The modes that have large vibration velocity at the thin waveguide tip are the odd number harmonic longitudinal modes from the thin waveguide [10]. For low-frequency modes excitation, it was found that the matching issue is essential [13]. This matching issue states that when the resonant frequency of the longitudinal mode of the thin waveguide is not close to the resonant frequency of the double-parabolic-reflectors structure, large vibration velocity in the thin waveguide can be realized for that longitudinal mode. For high-frequency modes excitation, the high-power properties of the piezoelectric material such as large mechanical quality factor, large saturation vibration velocity, and low resonant frequency shift are important [13]. Since hard type PZTs have superior high-power properties than soft type PZTs, they
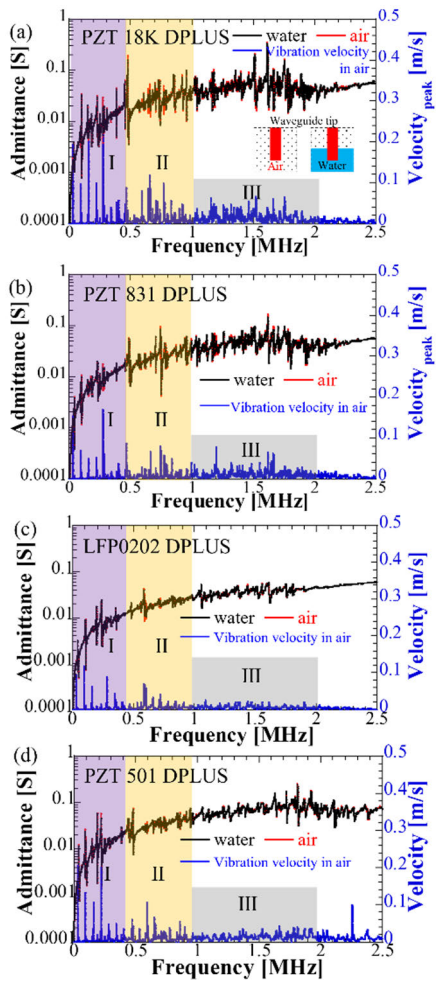
FIGURE 4. Frequency response of admittance and vibration velocity for (a)-(b) hard types and (c)-(d) soft types based DPLUS.

would be promising candidates for high-frequency and high-power operation of DPLUS. In the following, high-power properties of DPLUS with hard-type PZTs will be revealed.

Figure 4 shows the comparison of admittance and vibration velocity for hard types (Figs. 4(a)-4(b)) and soft types (Figs. 4(c)-4(d)) based DPLUS. Admittance of DPLUS was measured when the thin waveguide was at free condition (in air) and when the thin waveguide tip was immersed in water (1 mm as immersion depth). The measurement was conducted at 10 mV_{p-p} by a Precision Impedance Analyzer 4294A (Keysight, USA). Experimental setup for the vibration velocity measurement is shown in Fig. 5. Frequencies with large admittance changes between air and water conditions indicate large vibration velocity at the thin waveguide tip, and these frequencies are the subjects for comparison. Approximately 30 harmonic longitudinal modes from the thin waveguide can be counted for each DPLUS between 20 kHz to 2 MHz. For detailed comparison of the vibration velocity, the frequency range was divided into three regions: 0-0.4 MHz (region I), 0.4-1 MHz (region II), and 1-2 MHz (region III). Qualitatively speaking, in the region I,
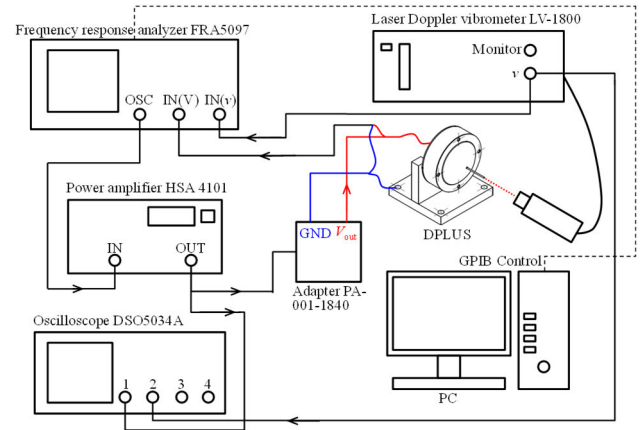

FIGURE 5. Experimental setup for measuring the frequency response of vibration velocity. First, the oscillation signal produced by FRA was amplified by a power amplifier. Then, the amplified signal was delivered to DPLUS through an adapter. The vibration velocity was then measured by an LDV. The applied voltage and vibration velocity were both monitored on an oscilloscope. The applied voltage amplitudes and vibration velocity amplitudes were recorded by FRA, and these results were extracted through PC.

the vibration amplitudes for different piezoelectric materials based DPLUS were comparable; in the region II, PZT types were superior to the lead-free type; in the region III, hard-type PZTs had the largest vibration amplitudes.

Modes at three regions were detailly compared by measuring the frequency response of vibration velocity at high input voltages. The applied voltage has an interval of 10 V_{p-p} and the maximum of 120 V_{p-p}. The measurement point was at the center of the thin waveguide tip. Experimental setup is the same as Fig. 5. The sweep time for the measurement was around 15 seconds at each applied voltage. This set was to ease the resonant frequency shift caused by the temperature increase during long-time operation of DPLUS. From the measurement results, the frequency with the largest vibration amplitude at each applied voltage was identified as the resonant frequency; the vibration amplitude at the resonant frequency and the shifts of the resonant frequency were obtained.

In regions I and II, the 1st (31 kHz), 15th (466 kHz) (or 19th (590 kHz)), 27th (836 kHz) harmonic longitudinal modes were selected for DPLUS with hard-type PZTs. In the region III, the following resonant frequencies were selected: around 1.154, 1.322, 1.528 MHz for PZT 18K type DPLUS, and around 1.198, 1.624, 1.665 MHz for PZT 831 type DPLUS. The selected frequencies include the largest vibration velocity between 1 to 2 MHz for each DPLUS. Measurement results are shown in Figs. 6-7. In the region I as shown in Fig. 6(a), the maximum peak vibration velocity was around 7.5 m/s, which is similar for DPLUS with different types of piezoelectric materials. Over 7.5 m/s could not be measured because the vibration of the thin waveguide became unstable and lateral vibration could be clearly observed. This up limit of vibration velocity might come from the vibration nonlinearity of the metal material. From the result as shown
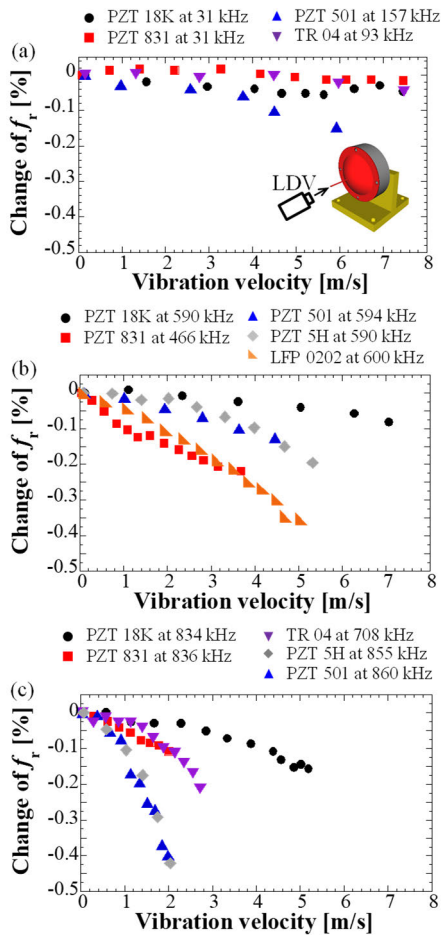
FIGURE 6. Resonant frequency shifts against vibration velocity for the modes in (a) region I and (b)-(c) region II. The vibration velocity was measured in air.

FIGURE 7. Resonant frequency shifts against vibration velocity for the modes in (a)-(b) region III. Purple areas represent that the vibration amplitudes of hard-type PZTs based DPLUS surpassed those of soft types. The vibration velocity was measured in air.

in Figs. 6(b)-6(c), PZT 18K type DPLUS had the largest vibration velocity, but PZT 831 type DPLUS had close results compared with soft types. For the modes in regions I and II (especially I), hard-type PZT based DPLUS had similar maximum vibration velocity compared with soft types.

Figure 7 shows the following phenomena: hard-type PZT based DPLUS had larger vibration velocity, and the maximum vibration velocity was around 1.15 to 7 times of those of the soft types; the slopes of the resonant frequency shifts for hard types were smaller. Superior high-power properties of DPLUS using hard-type PZT can be found in the region III. Maximum peak vibration velocity was around 7 m/s, which is 3.5 times of that of the DPLUS with soft-type piezoelectric materials (2 m/s). From Figs. 7(a)-7(b), it can also be observed that PZT 18K DPLUS had larger vibration velocity than PZT 831 DPLUS at ~1.6 MHz but smaller vibration velocity at ~1.1 MHz. It is caused by the resonant frequency matching issue as discussed in the reference [13]: the resonant frequency of the DPLUS parabolic structure (without a thin waveguide) can be equal to or close to the odd-number harmonic resonant frequency of the thin waveguide,
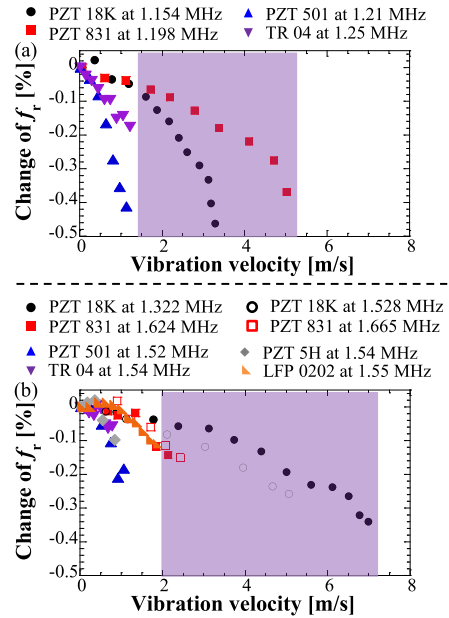
and this phenomenon shows the decrease of the vibration velocity in the thin waveguide compared with the case when two resonant frequencies are far from each other. To realize large vibration velocity in the thin waveguide, the resonant frequency matching should be avoided, i.e., the two resonant frequencies should be designed away from each other. The PZT 831 DPLUS at ~1.6 MHz has similar resonant frequencies for the DPLUS parabolic structure and the thin waveguide, and therefore has less vibration velocity than PZT 18K DPLUS. In Figs. 6(b)-6(c), the reason that PZT 831 type DPLUS had close results with those of soft types can also be explained by the resonant frequency matching issue: the vibration velocity in the thin waveguide is reduced when the resonant frequencies of the DPLUS parabolic structure and the thin waveguide are equal or similar. The decrease of the vibration velocity is caused by the voltage division by the equivalent inductors of the DPLUS parabolic structure and the thin waveguide, which can be understood from the equivalent circuit model in our previous work [13]. The effects on the vibration velocity by the resonant frequency matching issue and the high-power properties of the piezoelectric material are combined for PZT 831 type DPLUS in the frequency range as shown in Figs. 6(b)-6(c), and therefore the vibration velocity shows close results to those of soft types. For DPLUS with any type of piezoelectric material, to excite a specific harmonic mode of the thin waveguide with a large vibration velocity, the thin waveguide should be designed based on the resonant frequency matching issue. In summary, hard-type PZTs based DPLUS with superior high-power properties can be found between 1 to 2 MHz. PZT 18K DPLUS was considered as the best candidate for realizing high-frequency and high-power vibration output.

C. VIBRATION VELOCITY IN WATER

For the vibration velocity measurement in the previous sections, the thin waveguide was at free condition (in air). Adding a load to the thin waveguide can change the vibration characteristics, such as the shift of the resonant frequency and the decrease of tip vibration velocity. In this section, we explored the vibration characteristics of PZT 18K type DPLUS under the load of water.

Admittance of DPLUS was measured when the thin waveguide was immersed in water with different immersion depths d (2 mm and 4 mm) as illustrated in Fig. 8(a). The admittance under such loading conditions was then compared with the case when the DPLUS was at free condition (in air). Since the vibration velocity at the thin waveguide tip was difficult to measure when immersed in water, only the vibration velocity at the air condition was measured. The measured admittance curves were fitted to evaluate the vibration velocity under the loading conditions. The fitting model was based on the equivalent circuit as shown in Fig. 8(b). Under different loading conditions, the currents i_m were calculated. The vibration velocity v can be calculated by the following equation

$$v = \frac{i_m}{A} \qquad (2)$$

where A is the force factor. The value of A was assumed as a constant under different loadings. Then, the vibration velocity v under different immersion depths d is proportional to the current i_m. For example, let us assume the current i_m and velocity v at free condition are both 1, then if the current decreases to 0.3 when d is 2 mm, the velocity would also be reduced to 0.3. Therefore, the vibration velocity can be estimated by comparing the i_m under different d.

For PZT 18K type DPLUS, four resonant frequencies were selected: around 31 kHz, 590 kHz, 1.154 MHz, and 1.322 MHz. Measured and fitted admittance curves were plotted in Figs. 9-10. In the experiment, admittance was measured at 10 mV$_{p-p}$ under three conditions: air condition and the conditions where the immersion depth d was around 2 mm and 4 mm. For around 31 kHz, when the immersion depth is 4 mm was not measured. Vibration velocity at the air condition was measured at 1 V$_{p-p}$. For fitted results, admittance and vibration velocity under three conditions were given; the vibration velocity was normalized to the maximum vibration velocity in the air condition. As shown in Figs. 9(a)-9(d) and 10(a)-10(d), with increasing the immersion depth d, peak admittance values and resonant frequencies were both decreased. For the fitted vibration velocity, a value was given to indicate the maximum vibration velocity change when the immersion depth d was 2 mm. Approximately 66.7%, 85%, 100%, and 36% of vibration velocity were obtained for 31 kHz (Fig. 9(b)), 590 kHz (Fig. 9(d)), 1.154 MHz (Fig. 10(b)), and 1.322 MHz (Fig. 10(d)), respectively, compared with the maximum vibration velocity in the air condition. Under high voltages, if we assume the same percentages could be obtained, the maximum peak vibration
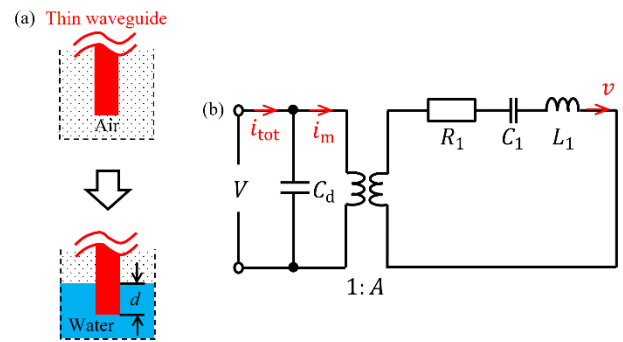

FIGURE 8. (a) Illustration for the admittance measurement under different loading conditions. (b) The equivalent circuit for fitting the measured admittance curves.

TABLE 3. Maximum vibration velocity at the longitudinal direction of the thin waveguide tip and maximum acoustic pressure in water. Results were obtained for PZT 18K type DPLUS.

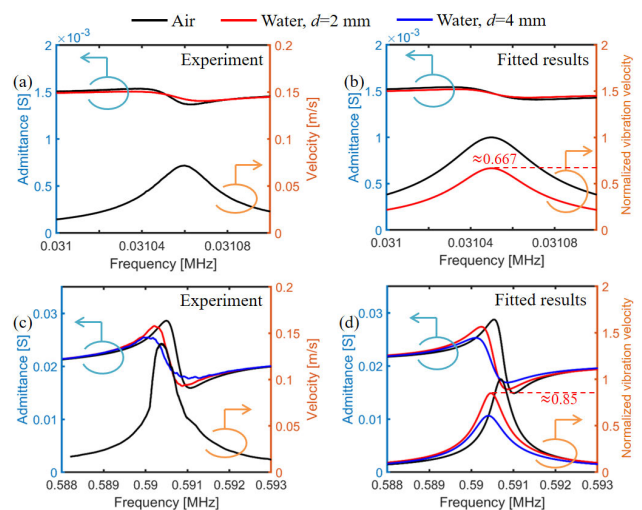|	31 kHz	590 kHz	1.154 MHz	1.322 MHz
v_{max} (m/s)	4.94	6.00	2.85	2.50
P_{max} (MPa)	0.46	10.0	7.70	7.20

FIGURE 9. Measured and fitted admittance curves of PZT 18K type DPLUS under different loading conditions. The examined frequencies were around (a)-(b) 31 kHz and (c)-(d) 590 kHz. The thin waveguide was immersed in water with different depths d. The vibration velocity in the fitted results were normalized to its maximum vibration velocity in air.

velocity v_{max} in water would be as listed in Table. 3. The values of v_{max} were calculated as the product of the percentages and the measured maximum vibration velocities in air (shown in Figs. 6-7). By using the maximum vibration velocity in water, sound field in water can be explored.

D. SOUND FIELD IN WATER

The scalar-field sound pressure in water by the ultrasonic vibration can be calculated by the Rayleigh-Sommerfeld diffraction integral. Here, the discretization method was adopted [6], [14], as illustrated in Fig. 11. The vibration
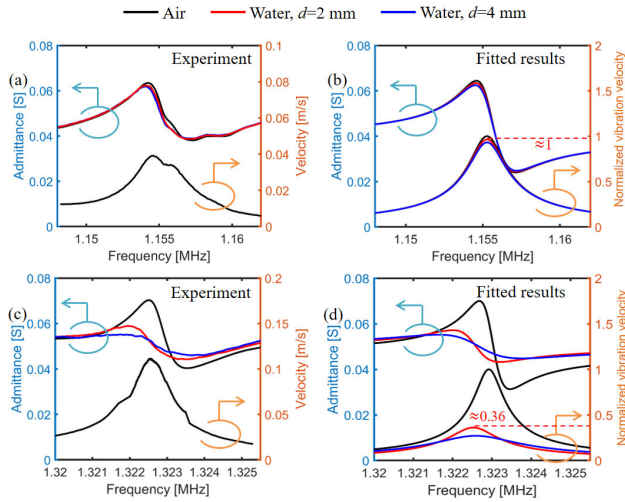
FIGURE 10. Measured and fitted admittance curves of PZT 18K type DPLUS under different loading conditions. The examined frequencies were around (a)-(b) 1.154 MHz and (c)-(d) 1.322 MHz.
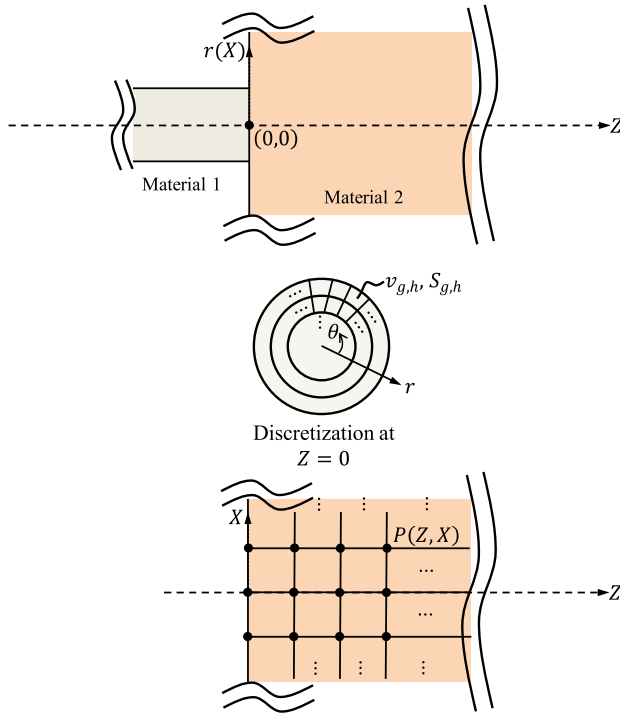

FIGURE 11. Discretization of the vibration source for calculating the sound field.

source (the cross-section at the thin waveguide tip) was discretized into small elements and the acoustic pressure at the observation point is the total contribution from elemental areas of the vibration source. The total pressure at the observation point (Z, X) was calculated by

$$P(Z, X) = \left| j\rho c_0 \sum_{g=1}^{m} \sum_{h=1}^{n} \frac{S_{g,h} v_{g,h}}{\lambda} \frac{e^{-j\frac{2\pi f}{c_0} l_{g,h}}}{l_{g,h}} \right| \quad (3)$$

where m and n are numbers of discretized elements in radial and circular directions of the vibration source, g and h are the identities of each element, ρ and c_0 are the density and sound velocity of water, f and λ are the ultrasonic frequency and the wavelength in water, $S_{g,h}$ is the area of each element, $v_{g,h}$ is the vibration velocity of each element, $l_{g,h}$ is the distance from the element to the observation point. Acoustic attenuation in water was not considered in the calculation. The DPLUS thin waveguide radius a is 0.5 mm, ρ and c_0 are 1000 kg/m^3 and 1496 m/s. The vibration source was assumed as a piston source. This assumption is reasonable after considering the vibration shapes of the propagating wave in the DPLUS thin waveguide.

The maximum vibration velocities listed in Table. 3 were used as $v_{g,h}$ to calculate the sound pressure. The calculated results for 31 kHz, 590 kHz, 1.154 MHz, and 1.322 MHz are shown in Figs. 12(a)-12(d), respectively. Ten contour lines were shown in each figure. The acoustic pressure distributions were not complicated because the ratio a/λ (thin waveguide radius/wavelength) is less than 0.5. With increasing the frequency, the contour lines behaved more like cigar shapes, and the spread of the ultrasound wave was less. Maximum acoustic pressure was around 10 MPa at 590 kHz. Above 1 MHz, large acoustic pressure could also be obtained: 7.7 MPa and 7.2 MPa at 1.154 MHz and 1.322 MHz, respectively. These acoustic pressure magnitudes were summarized in Table. 3. The values would be large enough to produce acoustic cavitation considering the cavitation thresholds. Results proved that DPLUS with hard-type PZTs are very promising for high-power ultrasound applications since large acoustic pressure at a wide frequency range can be obtained.

The effectiveness of our method for estimating the vibration velocity and acoustic pressure was further verified by the acoustic pressure measurement. A needle-type hydrophone HY05N (Toray Engineering Co., Ltd, Tokyo, Japan) was used to measure the axial acoustic pressure produced by the PZT 18K type DPLUS near 1.322 MHz. High acoustic pressure cannot be measured with this hydrophone, so the applied voltage to DPLUS was around 5 V$_{p-p}$. Based on the method described in Section C, the estimated peak vibration velocity under the immersion depth 2 mm was approximately 0.16 m/s (at 1.322 MHz), and this vibration amplitude was used as $v_{g,h}$ in calculating Eq. 3. The axial acoustic pressure by calculation and experiment were plotted in Fig. 13. The results showed overall decreasing tendencies. Experimental results were smaller than calculation, one possible reason is the spatial averaging effect in the hydrophone measurement [15]. The calculated results considering the spatial averaging effect were also plotted. The averaging area was $\pi \times 0.25^2$ mm^2, which was calculated based on the effective radius of the piezoelectric material at the hydrophone tip (0.25 mm). When the axial distance is less than 1 mm, the spatial averaging effect would have large influence. In the experiment, when the axial distance is less than 1 mm, the sound field between the thin waveguide tip and the hydrophone tip was
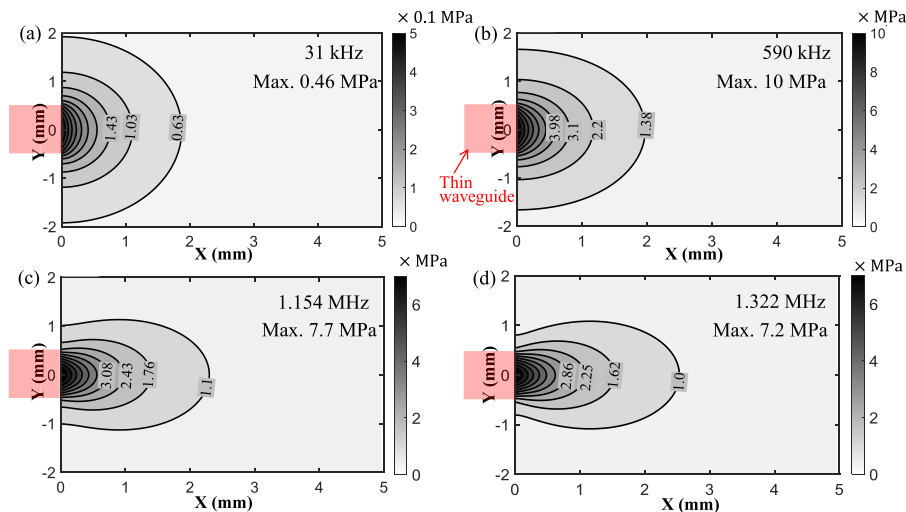
FIGURE 12. Estimated maximum acoustic pressure in water by solving the Rayleigh-Sommerfeld diffraction integral. Results for (a) 31 kHz, (b) 590 kHz, (c) 1.154 MHz, and (d) 1.322 MHz.
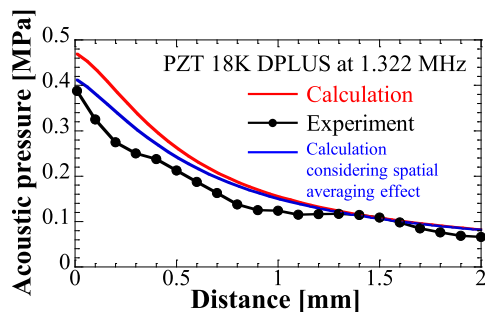

FIGURE 13. Results of the axial acoustic pressure.

complicated because their diameters were large: 1 mm for thin waveguide tip and 1.4 mm for thin hydrophone tip. The reflected wave from the hydrophone tip can interfere with the emitted wave from the thin waveguide tip. When the axial distance is larger than 1 mm, the spatial averaging effect had no effect based on the calculation, and the measured results for 1.322 MHz were close to the calculation at such axial distance. Therefore, experimental results indicate the close vibration velocity at the vibration source compared with the calculation, which is ∼0.16 m/s. Based on our measurement results, the estimation method for the vibration velocity and acoustic pressure in water is effective, and the estimated vibration velocity and acoustic pressure as listed in Table 3 are valid.

IV. CONCLUSION
In this paper, the wide-frequency (20 kHz-2 MHz) high-power vibration characteristics of DPLUS with hard-type PZT were revealed. Under non-resonant excitation of the DPLUS waveguide, the piezoelectric constant e_{33} and thickness d of the piezoelectric ring were proved to be important indexes for determining the vibration output at the thin waveguide tip. However, soft-type piezoelectric materials were found effective. Under resonant excitation of the DPLUS waveguide, high-power vibration characteristics of hard-type PZT DPLUS can be found between 1 to 2 MHz. Maximum vibration velocity of hard-type PZT DPLUS (7 m/s) was around 3.5 times of soft types (2 m/s) between 1 to 2 MHz. (Hard-type) PZT 18K DPLUS showed the best vibration characteristics: for the fundamental thin waveguide longitudinal mode resonant frequency at 31 kHz, the maximum peak vibration velocity was 7.5 m/s and this maximum value was found independent on the type of piezoelectric materials; for the selected five resonant frequencies between 0.4 to 2 MHz, maximum peak vibration velocity of 7 m/s was realized and the resonant frequency shifts were the smallest. By fitting the measured admittance under different immersion depths, vibration velocity at the thin waveguide tip was estimated. Under the immersion depth of 2 mm, the maximum acoustic pressure values calculated by the Rayleigh-Sommerfeld diffraction integral were as follows: around 0.46 MPa (at 31 kHz), 10 MPa (at 590 kHz), 7.7 MPa (at 1.154 MHz), and 7.2 MPa (at 1.322 MHz). The effectiveness of this estimation was also verified by the acoustic pressure measurement at a low input voltage. These results showed that DPLUS with hard-type PZT can achieve wide working frequency (20 kHz to 2 MHz) and high-power output (10 MPa), which is impossible for some conventional transducers such as Langevin transducers and HIFU transducers. Therefore, DPLUS can become a suitable candidate for examining and opening up new ultrasonic applications.

REFERENCES
[1] J. E. Kennedy, "High-intensity focused ultrasound in the treatment of solid tumours," *Nature Rev. Cancer*, vol. 5, pp. 321–327, May 2005.

[2] W. Kreider, P. V. Yuldashev, O. A. Sapozhnikov, N. Farr, A. Partanen, M. R. Bailey, and V. A. Khokhlova, "Characterization of a multi-element clinical HIFU system using acoustic holography and nonlinear modeling," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 60, no. 8, pp. 1683–1698, Aug. 2013.

[3] G. Harvey, A. Gachagan, and T. Mutasa, "Review of high-power ultrasound-industrial applications and measurement methods," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 61, no. 3, pp. 481–495, Mar. 2014.

[4] P. Ciuti, N. V. Dezhkunov, A. Francescutto, A. I. Kulak, and G. Iernetti, "Cavitation activity stimulation by low frequency field pulses," *Ultrason. Sonochem.*, vol. 7, no. 4, pp. 213–216, Oct. 2000.

[5] A. H. Barati, M. Mokhtari-Dizaji, H. Mozdarani, Z. Bathaie, and Z. M. Hassan, "Effect of exposure parameters on cavitation induced by low-level dual-frequency ultrasound," *Ultrason. Sonochem.*, vol. 14, no. 6, pp. 783–789, Sep. 2007.

[6] H.-L. Liu and C.-M. Hsieh, "Single-transducer dual-frequency ultrasound generation to enhance acoustic cavitation," *Ultrason. Sonochem.*, vol. 16, no. 3, pp. 431–438, Mar. 2009.

[7] J. Yasuda, A. Asai, S. Yoshizawa, and S. I. Umemura, "Efficient generation of cavitation bubbles in gel phantom by ultrasound exposure with negative-followed by positive-peak-pressure-emphasized waves," *Jpn. J. Appl. Phys.*, vol. 52, Jul. 2013, Art. no. 07HF11.

[8] K. Chen, T. Irie, T. Iijima, and T. Morita, "Acoustic focusing to the waveguides utilizing double parabolic reflectors," *Appl. Phys. Lett.*, vol. 114, no. 7, Feb. 2019, Art. no. 072902.

[9] K. Chen, T. Irie, T. Iijima, and T. Morita, "Double-parabolic-reflectors acoustic waveguides for high-power medical ultrasound," *Sci. Rep.*, vol. 9, no. 1, p. 18493, Dec. 2019.

[10] K. Chen, T. Irie, T. Iijima, and T. Morita, "Wideband multimode excitation by a double-parabolic-reflector ultrasonic transducer," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 67, no. 8, pp. 1620–1631, Aug. 2020.

[11] Q. Y. Liu, K. Chen, J. H. Hu, and T. Morita, "An ultrasonic tweezer with multiple manipulation functions based on the double-parabolic-reflector wave-guided high-power ultrasonic transducer," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 67, no. 11, pp. 2471–2474, Nov. 2020.

[12] K. Chen, T. Irie, T. Iijima, and T. Morita, "Double-parabolic-reflectors ultrasonic transducer with flexible waveguide for minimally invasive treatment," *IEEE Trans. Biomed. Eng.*, vol. 68, no. 10, pp. 2965–2973, Oct. 2021.

[13] K. Chen, T. Irie, T. Iijima, T. Kasashima, K. Yokoyama, and T. Morita, "Selection criteria of piezoelectric materials for double-parabolic-reflectors ultrasonic transducers (DPLUS) for high-power ultrasound," *Jpn. J. Appl. Phys.*, vol. 60, no. 10, Oct. 2021, Art. no. 106504.

[14] J. Zemanek, "Beam behavior within the nearfield of a vibrating piston," *J. Acoust. Soc. Amer.*, vol. 49, no. 1B, pp. 181–191, Jan. 1971.

[15] G. Xing, P. Yang, L. He, and X. Feng, "Spatial averaging effects of hydrophone on field characterization of planar transducer using Fresnel approximation," *Ultrasonics*, vol. 71, pp. 51–58, Sep. 2016.

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