Harvesting low-frequency acoustic energy using multiple PVDF beam arrays in quarter-wavelength acoustic resonator

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A B S T R A C T

An acoustic energy harvester is introduced that uses a quarter-wavelength straight-tube acoustic resonator with polyvinylidene fluoride (PVDF) piezoelectric cantilever beams placed inside the resonator. When the tube is excited by an incident wave at its first acoustic eigenfrequency, an amplified acoustic resonant standing wave is developed inside the tube. The acoustic pressure gradient of the amplified standing wave then drives the vibration motion of the PVDF piezoelectric beams, generating electricity due to the direct piezoelectric effect. In order to maximize the amount of the harvested energy, each PVDF piezoelectric beam has been designed to have the same structural eigenfrequency as the acoustic eigenfrequency of the tube. With a single PVDF beam placed inside the tube, the harvested voltage and power become the maximum near the tube open inlet where the largest acoustic pressure gradient vibrates the PVDF beam. As the beam is moved to the tube closed end, the voltage and power gradually decrease due to the decreased acoustic pressure gradient. Multiple piezoelectric beams have been placed inside the tube with two different configurations: the aligned and zigzag configurations. With the zigzag configuration which has the more open path for acoustic air particle motions, the significant increases in the harvested voltage and power have been observed. Due to the interruption of acoustic air particle motion caused by the beams, it is found that placing PVDF beams near the closed tube end is not beneficial. The total output voltage of the piezoelectric beams increases linearly as the incident sound pressure increases.

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1. Introduction

In the past decade, a variety of energy sources in environment including radiant (e.g., solar [1,2]), mechanical (e.g., wind [3,4] and vibration [5,6]), thermal [7,8] and biochemical [9,10] energy, have been investigated as potential sources for energy harvesting. Although there have been significant efforts in developing environmental energy harvesting technologies, our environment is still full of wasted and unused energy. Acoustic energy is one example of these currently wasted energies. Compared with other energy sources, insignificant efforts have been devoted to developing acoustic energy harvesting methods. Since acoustic energy is a clean, ubiquitous, and sustainable energy source and a significant amount of acoustic energy is available in some circumstances (for example, airports, construction sites, factory, etc.), it is of great interest to investigate acoustic energy harvesting mechanisms.

Horowitz et al. [11] first introduced a micromachined acoustic energy harvester using a Helmholtz resonator with a piezoelectric back plate. The resonator was excited by an incident wave with a power level (SPL) of 149 dB (referenced 20 μPa) at 13.6 kHz. Liu et al. [13–15] developed an electromechanical Helmholtz resonator which utilized a uniform acoustic pressure in a resonator chamber to bend a piezoelectric back plate. The resonator was excited by an incident SPL of 160 dB at 2.6 kHz, generating a maximum output power of 30 mW which could be enough to supply energy to low power electronics. Kim et al. [16] also used a Helmholtz resonator in which a permanent magnet/coil system was driven by acoustic pressure to harvest airflow and aeroacoustic energy. An output voltage of 4 mV was measured with an input pressure of 0.2 kPa (i.e., 140 dB SPL) at 1.4 kHz. In addition to Helmholtz resonators, periodic structures have been used to confine acoustic waves [17–19]. Wu et al. [20–22] used a disordered structural pattern in a sonic crystal to trap acoustic waves and to amplify sound pressure. By placing a curved PVDF piezoelectric beam inside the disordered structural pattern, the amplified sound pressure excited the beam and an output power of ~35 nW was harvested from an incident wave with ~90 dB at 4.2 kHz. Lastly, piezoelectric zinc oxide nanowires were used to harvest ultrasonic waves to power nanodevices and nanosystems [23].
Most previous studies have focused on harvesting acoustic energy at relatively high frequencies ranged from a few kHz to MHz. However, sound sources available in everyday life contain predominantly low frequency components due to their lower spatial attenuation rates, compared with high frequency sound [24]. Therefore, it is necessary to develop an innovative mechanism to harvest low-frequency acoustic energy. In this article, a quarter-wavelength straight-tube acoustic resonator with PVDF piezoelectric cantilever beams is proposed to harvest acoustic energy from travelling sound waves at a low frequency. The length of the tube is 58 cm and its corresponding first acoustic eigenfrequency is 146 Hz. The harvesting frequency can be easily tuned by changing the tube length. When the tube is excited by an external sound wave at its eigenfrequency, a resonant standing wave is developed inside the tube. When PVDF cantilever beams are placed perpendicular to the tube axis, the resonant standing wave excites the vibration motion of the PVDF piezoelectric beams, resulting in the generation of electricity.

This paper is organized as follows. In Section 2, the acoustic resonant behavior of quarter-wavelength resonator and the mechanism to convert acoustic energy to electrical power are presented. Experimental apparatus and procedures are discussed in Section 3. In Section 4, the output voltage and power with a single PVDF beam and multiple PVDF beams are discussed. Conclusions are drawn in the last section.

2. Acoustic energy harvesting mechanism

2.1. Acoustic resonance of quarter-wavelength resonator

Acoustic resonators such as half-wavelength, quarter-wavelength, and Helmholtz resonators, as shown in Fig. 1, have been used for both sound augmentation in musical instruments [25] and noise attenuation in industrial applications, for example, ducts [26,27], buildings [28], fans [29], etc. When these resonators are excited by an incident wave at their acoustic resonant frequencies, acoustic energy is collected inside the resonators in a form of standing resonant waves. The efficiency of collecting acoustic energy inside half and quarter-wavelength resonators has been studied experimentally in terms of sound attenuation outside the resonators [30]. It was found that a quarter-wavelength resonator collects acoustic energy about three time more than a half-wavelength resonator at a given diameter and frequency. Compared with a Helmholtz resonator, a quarter-wave resonator requires less volume to collect the same amount of acoustic energy at a given frequency [30]. Therefore, a quarter-wavelength resonator is expected to be the best design amongst these resonators to collect acoustic energy in a closed space.

A typical Helmholtz resonator consists of a neck and a cavity as shown in Fig. 1a. For the first eigenmode, the air in the neck oscillates as a mass while the static air in the cavity undergoes compression and expansion as a spring. Including energy dissipations (e.g., the sound radiation from the open neck and the friction between air particles and resonator walls), the Helmholtz resonator can be modeled as a mass-spring-damper system [24]. Assuming the wavelength of an incident wave is much larger than the dimensions of Helmholtz resonator, the first eigenfrequency $f_1$ can be obtained from the lumped element model as [24,31]

$$f_1 = \frac{c_0}{2\pi \sqrt{\frac{S}{V}}},$$

(1)

where $c_0$ is the sound speed, $S$ is the cross-sectional area of the neck, $V$ is the cavity volume, and $l$ is the effective neck length including the end corrections. When the resonator is excited at $f_1$, the sound pressure in the cavity is resonantly amplified. The amplification ratio $A$ of the cavity pressure to the incident pressure is represented as [24]

$$A = \frac{P_{\text{cavity}}}{P_{\text{incident}}} = 2\pi \sqrt{\frac{lV}{S^2}}.\tag{2}$$

From Eqs. (1) and (2), in order to lower the eigenfrequency and increase the amplification ratio, a Helmholtz resonator with a large chamber volume and a long narrow neck is preferred. As shown in Eq. (2), however, the neck length and cross-sectional area predominate the cavity volume in the amplification ratio. Therefore, in designing a small harvester, it is desired to have a resonator with long and narrow dimensions, such as a quarter-wavelength tube resonator [32].

Unlike the Helmholtz resonator, a quarter-wavelength resonator shown in Fig. 1c cannot be modeled as lumped elements since its longitudinal dimension is not much smaller than the wavelength. In the quarter-wavelength resonator, the longitudinal particle velocity $u(z,t)$ and acoustic pressure $p(z,t)$ at the $n$-th resonant mode are represented as sinusoidal functions [33]

$$u(z,t) = u_0 \cos\left(\frac{2(n-1)z}{2L}\right) \exp(i2nf_n t),\tag{3}$$

$$p(z,t) = p_0 \sin\left(\frac{2(n-1)z}{2L}\right) \exp(i2nf_n t). \tag{4}$$

where $L$ is the tube length which is equal to $(2n - 1)l/4$, $z$ is the distance measured from the tube open inlet, $f_n$ is the eigenfrequency, and $n$ is the mode number, $n = 1, 2, 3,...$ At the first eigenmode (i.e., $n = 1$), the tube length is equal to a quarter wavelength, $L = l/4$. From Eqs. (3) and (4), the maximum magnitude of particle velocity $u_0$ occurs at the tube open inlet while the acoustic pressure reaches the maximum magnitude $p_0$ at the closed end of tube.

2.2. Acoustic energy conversion by piezoelectric beam inside tube resonator

When a clamped-free piezoelectric beam is placed inside the tube resonator, the spatially varying acoustic resonant pressure in Eq. (4) induces the pressure difference between each side of the beam as shown in Fig. 2. The pressure difference $\Delta p$ drives the vibration motion of the piezoelectric beam at the frequency $f_n$, resulting in generating electricity by the 31 piezoelectric mode. When a beam is placed near the tube inlet where the pressure gradient is at the maximum, a large displacement of beam will generate a high voltage.

Output power from piezoelectric energy harvesters strongly depends on the electrical impedance of external circuit [15,20,34,35]. Most previous studies have focused on the optimized loading resistance and output power of a cantilever beam driven by a base excitation [34,36]. In this study, the optimized loading resistance and output power for a cantilever beam excited by acoustic pressure difference $\Delta p$ are obtained as following. The equivalent circuit model for mechanical and electrical elements of a piezoelectric cantilever beam can be described by Kirchoff’s Voltage Law (KVL) [34,37]
The cantilever beam with distributed mass under an input stress and \( D_g \) can be regarded as the average bending stress to inertial, damping, stiffness, and piezoelectric elements, respectively. The input stress \( \sigma_{in} \) can be regarded as the average normal stress induced by bending moment \( M_b(x) \) as

\[
\sigma_{in} = \frac{1}{l} \int_0^l M_b(x) \text{d}x, \tag{6}
\]

where \( I \) is the moment of inertia, \( t_c \) is the distance from the neutral axis to the center of the piezoelectric layer. \( M_b(x) \) is the bending moment generated by the acoustic pressure difference \( \Delta p \). In order to obtain \( \sigma_i, \sigma_d, \sigma_s, \text{ and } \sigma_p \), the cantilever beam with distributed mass under uniform acoustic pressure in Fig. 3a is simplified to the beam with a point mass under a concentrated force in Fig. 3b.

The equivalent point mass in Fig. 3b can be obtained by equating kinetic energy for both systems. The displacement for the cantilever beam with distributed mass under \( \Delta p \) is expressed as [38]

\[
\nu(t, x) = \frac{b x^2 (6l^2 + 4lx + x^2)}{24EI} \Delta p, \tag{7}
\]

where \( E \) is the Young’s modulus and \( b \) is width of the beam. A differential element \( dx \) contains kinetic energy as

\[
dG_k = \frac{1}{2} \frac{d\nu^2}{t_p} \text{d}x. \tag{8}
\]

Kinetic energy can be obtained by integration over the beam length \( l \) as

\[
G_k = \int_0^l dG_k = \frac{1}{2} 0.257m. \tag{9}
\]

Therefore, the equivalent point mass is \( m_{eq} = 0.257m \). The induced stress to each element are given as

\[
\begin{align*}
\sigma_i &= \frac{m_{eq} \ddot{x}}{c_1}, \\
\sigma_d &= \frac{\eta \ddot{x}}{c_2}, \\
\sigma_s &= \frac{E \delta}{c_3}, \\
\sigma_p &= \frac{-dE}{t_p} V,
\end{align*}
\]

where \( \delta \) is strain, \( t_p \) is the thickness of piezoelectric material, the damping coefficient is \( \eta = 2\zeta\omega_n m_{eq} c_2 c_1 \) with a damping ratio \( \zeta \) and the geometric constants \( c_1 = 3lI^2 \) and \( c_2 = 3t(l/2)^2 \). Substituting Eqs. (6), (10), (11), (12), (13) into Eq. (5) gives the magnitude of output voltage as a function of \( \Delta p \) as

\[
\begin{align*}
V_{mag} &= \frac{\omega_n RC_p dt_p / \varepsilon}{\sqrt{R^2 C_p^2 (\frac{4 \omega_n^2 (4c_2^2 + k^2)}{4c_2^2} + \frac{4c_2^2 + 4k^2}{4k^2} \omega_n RC_p} \left( \frac{t_f^2 b}{6l} \right)}} \Delta p. \\
\end{align*}
\]

where \( k \) is the piezoelectric coupling coefficient, \( d \) is the piezoelectric constant, \( C_p \) is the piezoelectric capacitance, \( R \) is the loading resistance, and \( \varepsilon \) is the permittivity. Then, the output electric power \( P \) is given as

\[
P = \frac{V_{mag}^2}{R} \\
= \frac{\left( (\omega_n dt_p / \varepsilon)^2 / RC_p \right)^2}{\left( \omega_n^2 R^2 C_p^2 (4c_2^2 + k^2) + 4c_2^2 + 4k^2 \omega_n RC_p \right) \left( \frac{t_f^2 b}{6l} \Delta p \right)^2}. \tag{15}
\]

The amount of harvested power can be maximized when \( \partial P / \partial R = 0 \). The optimized resistance can be obtained as

\[
R_{opt} = \frac{1}{\omega_n C_p} \left( \frac{2\zeta}{\sqrt{4\omega_n^2 + k^2}} \right). \tag{16}
\]

3. Experiments

A quarter-wavelength acoustic tube resonator has been fabricated using 1/2 in. thick polycarbonate plates as shown in Fig. 4. The tube is 58 cm long with a uniform rectangular cross-section of 4 cm \( \times \) 5 cm. Thick acoustical sealing caulk is applied between the gaps of the polycarbonate panels to minimize sound leakage. A premium powered loudspeaker (Audioengine 5 by Audioengine) driven by a data acquisition system (DAQ) NI-PCI 6289 is used to generate an incident sound wave. Quarter-inch condenser microphones (377C10 by PCB Piezotronics) powered by a sensor signal conditioner (482CS5 by PCB Piezotronics) are used to measure acoustic pressures at various positions along the tube.
In order to convert the acoustic energy inside the tube resonator, unimorph polyvinylidene fluoride (PVDF) piezoelectric cantilever beams (LDT-028k by Measurement Specialties) have been placed along the tube as shown in Fig. 4a. Each piezoelectric beam has been designed to have the same structural eigenfrequency as the acoustic eigenfrequency of the tube. Dimensions of piezoelectric beam are 2 cm in length, 1.61 cm in width, and 0.2 mm in thickness. The unimorph piezoelectric beam consists of a 30 μm thick PVDF film (14%), a 127 μm thick polyester laminate (62%), and an adhesive layer (24%). The bottom panel of the tube consists of several polycarbonate blocks which clamp the thin PVDF beams. The material properties of the PVDF films are provided in Table 1.

4. Results

4.1. Amplified resonant pressure in quarter-wavelength tube resonator

In order to verify the acoustic eigenmodes of tube resonator, the tube is excited by an incident sound of 100 dB and acoustic pressure is measured at various positions along the tube. Fig. 5 shows the magnitudes of the first three acoustic pressure eigenmodes normalized by the incident pressure magnitude along the tube. The first three eigenfrequencies are measured as \(f_1 = 146\) Hz, \(f_2 = 439\) Hz, and \(f_3 = 734\) Hz. The measured resonant acoustic pressures are well represented by the sinusoidal functions in Eq. (4) with the maximum magnitudes at the closed end of the tube. In a quarter-wavelength resonator, the amplification ratio can be defined as a ratio of the maximum pressure inside tube to the incident sound pressure \(p_{\text{incident}}\). As shown in Fig. 5, the largest amplification ratio is obtained as 59.1 for the first eigenmode and decreases as the mode number increases: 42.2 and 23.3 at the second and third eigenmodes, respectively. It suggests that the most acoustic energy is accumulated inside the tube at the first eigenmode, which is consistent with the results from Ref. [30].

4.2. Acoustic energy harvesting using single piezoelectric beam

A single PVDF beam has been placed at various positions inside the tube as shown in Fig. 6a. The first position \(A\) is located at 5 cm from the tube inlet and additional positions are set at 5 cm increments. The quarter-wavelength acoustic energy harvester is excited by an incident wave of 100 dB at the first eigenfrequency \(f_1 = 146\) Hz. Fig. 6b shows the output voltage and power generated by a single PVDF beam placed from positions \(A\) to \(J\). A maximum output voltage of 0.105 V is measured when the beam is placed at the position \(A\) near the inlet of the tube. As the PVDF beam moves toward the tube closed end, the output voltage decreases.

### Table 1

<table>
<thead>
<tr>
<th>Description and symbol</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td>Piezoelectric constant, (d_{31})</td>
<td>23 pC/N</td>
</tr>
<tr>
<td>Relative permittivity, (e/e_0)</td>
<td>12–13</td>
</tr>
<tr>
<td>Young’s modulus, (E)</td>
<td>2–4 GPa</td>
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<tr>
<td>Capacitance, (C_p)</td>
<td>5.5 nF</td>
</tr>
<tr>
<td>Coupling factor, (k)</td>
<td>0.12</td>
</tr>
<tr>
<td>Damping ratio, (\zeta)</td>
<td>0.05</td>
</tr>
</tbody>
</table>
gradually. This result is in line with the particle velocity $u$ in (3), which is proportional to the pressure gradient. Since the PVDF beam is placed in the spatially fluctuating pressure field, the pressure difference across the beam thickness causes the beam to bend along the $z$-direction, resulting in voltage generation. When the PVDF beam is placed near the tube inlet, where the pressure gradient is at the maximum, the largest output voltage is obtained by a large beam deflection. When the beam is placed near the tube closed end, the small pressure gradient induces a small beam deflection, although the pressure magnitude is at the maximum at the tube closed end.

From Eq. (4), assuming the pressure difference across the beam as

$$\Delta p = p_0 \left[ \sin \left( \frac{\pi (z_B + t_B/2)}{2L} \right) \right]$$

where $t_B$ and $z_B$ are the thickness and position of piezoelectric beam respectively, the voltage and power can be calculated from Eqs. (14) and (15) and are shown in Fig. 6b. The discrepancy between the experimental data and calculated results might be from neglecting the acoustic-structural interaction in the theoretical calculations. The actual driving force by the acoustic standing wave in the closed space of tube is different from the pressure difference of acoustic eigenmode which does not account for the presence of beams. It is analogous to the drag coefficient which relates a fluidic dynamic force with a drag force exerting on an immersed solid body in a fluid flow [39]. Further investigations are needed to understand the fluidic–acoustic–structural interaction in a closed space for better estimations.

4.3. Acoustic energy harvesting using multiple piezoelectric beams

In order to increase the output voltage and power, multiple PVDF beams have been placed in the tube. In this study, the beams have been placed in two different configurations: aligned and zigzag configurations. In the aligned configuration, all PVDF beams are placed along the centerline of tube as shown in Fig. 7a. In the zigzag configurations with the incident sound wave of 100 dB at 146 Hz.
zag configuration, the PVDF beams are placed in a zigzag pattern as shown in Fig. 7d. For both the configurations, the spacing between beams along the longitudinal tube axis is 5 cm. The output voltage with the aligned configuration is shown in Fig. 7b as a function of the number of piezoelectric beams placed in the tube. Piezoelectric beams are placed in the tube starting from the first position A near the open inlet to the last position J near the closed end. For example, the number of piezoelectric beams equal to 3 indicates that three beams are placed at the positions of A, B, and C. The voltage from each piezoelectric beam has been measured simultaneously and the total voltage is obtained by the summation of voltage from each beam assuming that all beams are connected in series.

For the aligned configuration as shown in Fig. 7b, the total output voltage increases as the number of beams increases until seven PVDF beams are placed at the positions A to G. A maximum total output voltage of 0.417 V has been measured. In addition to the seven beams at A through G, one or more additional beams at the positions H to J reduces the total output voltage. This is caused by the alteration of the acoustic resonance due to the additional beams near the tube closed end. In order to harvest more acoustic energy available in the resonator, it is desired to place more PVDF beams inside the tube. However, the presence of the beams in the tube reduces the acoustic resonant pressure by interrupting the air particle motion along the tube. This effect can also be seen in the case of the two beams at A and B. Comparing the first and second bars of Fig. 7b, the additional beam at the position B in addition to the beam at A, has decreased the voltage generated by the beam at A. Increasing the number of beams keeps reducing the voltage generated from each beam as shown in Fig. 7b.

To reduce the interference between the beams and air motion, the PVDF beams are placed in a zigzag pattern as shown in Fig. 7d. This configuration has more open path for air motion than the aligned configuration. The total output voltage in this zigzag configuration increases until nine PVDF beams are placed at the positions A through I (see Fig. 7d). The maximum voltage has been increased by 36.7% from 0.417 V to 0.570 V when compared with the aligned configuration in Fig. 7b. Also, the attenuation of the voltage generated by the first beam at A in the zigzag configuration is less than that in the aligned configuration. It can be concluded that the interference between the beams and air motion critically limits the maximum number of beams to obtain the maximum voltage.

From the measured voltage for each beam, the total power can be obtained as the summation of power from each beam. The estimated amounts of power using the aligned and zigzag configurations are shown in Fig. 7c and f, respectively. The maximum total power using the zigzag configuration is 248.5 nW, 45% higher than the maximum 171.4 nW of the aligned configuration. For both
beam configurations, the number of beams that generate the maximum power is five, which is smaller than that for the maximum voltage. In terms of the total power represented by the summation of $V^2/R$ from each beam, placing more piezoelectric beams also increases the total resistance. Therefore, placing the beams near the closed tube end, where the output voltage is relatively small, reduces the total power due to the increased resistance.

Fig. 8 shows the measured voltage from each piezoelectric beam in time domain when five piezoelectric beams are placed inside the tube resonator at the positions $A$ to $E$ in the aligned configuration (see Fig. 7a). It can be seen that the output voltages from individual piezoelectric beams are almost in the same phase, which indicates that all beams are vibrating in phase at their structural resonance.

Since placing additional PVDF beams near the tube closed end decreases the total power, the PVDF beams are placed only in the first half of the tube with the increased beam density as shown in Fig. 9a and d for the aligned and zigzag configurations, respectively. The first position $A$ is located at 2.5 cm from the tube inlet and additional positions are set at 2.5 cm increments in order to fill the half of the tube. The maximum output voltage increases significantly from 0.417 V and 0.570 V to 0.607 V and 0.696 V for the aligned and zigzag configurations, respectively. There are also significant increases in the maximum total power from 171.4 nW and 248.5 nW to 242.4 nW and 313.3 nW (45% and 26% increments) in the aligned and zigzag configurations, respectively. The corresponding power density is 0.0157 $\mu$W/cm² at 100 dB SPL, which is significantly higher than the previous acoustic energy harvesters [11,20,21], even at the lower operating frequency.

Fig. 10 shows the output voltage and power as a function of incident acoustic pressure using the five PVDF beams placed at the positions $A$ ($x = 2.5$ cm) through $E$ ($x = 12.5$ cm) in the zigzag configuration of Fig. 9d. The output voltage is linearly proportional to the incident acoustic pressure, which confirms that the driving force of beam deflections is the acoustic pressure gradient of resonant standing waves. The voltage of 1.48 V is measured with an incident pressure of 9 Pa (i.e., SPL = 110 dB). The corresponding estimated power is 2.2 $\mu$W and the power density of 0.11 $\mu$W/cm² is obtained at SPL = 110 dB.

5. Conclusion

The 58 cm long quarter-wavelength tube resonator with various piezoelectric beam array configurations has been studied to harvest low-frequency acoustic energy. The amplification ratio of 59.1 has been measured at the first eigenmode ($f_1 = 146$ Hz), and it decreases to 42.2 at $f_2 = 439$ Hz and 23.3 at $f_3 = 734$ Hz. In order to convert the first-eigenmode acoustic energy inside the tube, PVDF piezoelectric beams have been placed along the tube axis. With a single PVDF beam placed inside the tube, the voltage and power become the maximum near the tube open inlet where the largest acoustic pressure gradient vibrates the beam. The voltage and power gradually decrease as the beam is moved to the tube closed end. With the incident wave of 100 dB at $f_1 = 146$ Hz, the single PVDF beam near the tube inlet has generated the voltage of 0.105 V, which corresponds to the power of 55.6 nW. In order to increase the output voltage, multiple piezoelectric beams have been placed inside the tube with the aligned and zigzag configurations. Compared with the aligned configuration, the zigzag configuration significantly increases the voltage and power due to the more open path for acoustic air particle motion. It is observed that the number of beams to generate the maximum voltage is limited by the interruption of acoustic air particle motion caused by the beams. The maximum voltage and power have been obtained with beams placed in the first half of the tube resonator in the zigzag configuration, resulting in 0.696 V and 0.31 $\mu$W at the incident SPL of 100 dB. The voltage increases linearly with the incident sound pressure. At the incident SPL of 110 dB, the voltage of 1.48 V has been measured which corresponds to the power of 2.2 $\mu$W with the power density of 0.11 $\mu$W/cm².

References


