Research on excitation technology of high-throughput ultrasonic micro-separator based on micro-nano fabrication

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Abstract
The excitation technology of ultrasonic standing wave field is the core key to realize ultrasonic separation. This paper analyzes the excitation technology of (1, 1) mode ultrasonic separation of high-throughput ultrasonic micro-separator. There are two main problems: the coexistence of multiple modes in the separation cavity and the insufficient acoustic radiation force. In order to solve these two problems, this paper uses integrated circuit micromachining technology to process the ultrasonic micro-separator. The depth dimension of the cavity reaches 200 ± 0.5 µm, and the verticality of the side wall of the cavity reaches 83.36°. The degree of SFPD (Site Focal Plane Deviation) is less than or equal to 0.25 µm. Besides, this paper proposes an excitation method of saw-tooth frequency sweep of two anti-phase acoustic drivers. Finally, the experiments of the separator processed by the processing method proposed in this paper shows that, the excitation method proposed in this paper can effectively excite the (1, 1) mode, and shortens the time for the pattern formation of particle convergence, which greatly improves the separation efficiency. The separation throughput (flow rate) in one single cavity in this work can reach to 100 µl/min. It provides an effective basis for ultrasonic micro-separation technology.

Keywords
Micro-nano fabrication, ultrasonic, micro-separator

Introduction
Microfluidic ultrasound separation has been increasingly used in biomedical applications and has been successfully used for the separation of exotics and carbon tetrachloride from body fluids.¹ Acoustofluidic separation has important real-world implications in many biological targets because it is highly scalable, capable of manipulating bioparticles ranging in size from tens of nanometers to several hundred micrometers and it has high exosome integrity, unbiased isolation, no requirement of additional reagent and washing steps.¹ Ultrasonic separation is highly scalability, capable of manipulating biological particles from tens of nm to hundreds of microns, and has high outer small body integrity, unbiased separation, without additional reagents and washing steps. Ultrasonic devices are

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small and compatible with chip manufacturing processes, providing the possibility for the integration of ultrasonic separator, with a wide range of applications in the medical, chemical, and biological fields. With that being said, downsides such as low throughput and dependence on external equipment still impede successful commercialization from laboratory-based prototypes.

The studies on ultrasonic separation so far there are mainly two technologies of bulk acoustic wave (BAWs) and surface acoustic wave (SAWs). Both have been widely used to manipulate micro objects in the field of microfluidics. BAWs have been applied to microfluidic separations with many benefits, such as flexible placement of transducer, simple, and versatile setups. The research on excitation technology of Ultrasonic separation in this article is based on BAWs. Bulk acoustic waves (BAWs) are standing waves that propagate inside the resonant chamber of the microchannel. The transducer attached to the wall of the channel generates acoustic waves, which are supposed to propagate from the outside of the channel to form a standing wave. In order to form a stable ultrasonic standing wave field, the channel walls must be smooth and flat enough to act as a near-perfect reflector for sound waves. For the BAW-based devices, the microfluidic channel is typically made of materials with high acoustic impedances, such as silicon, glass, or stainless steel. Because of the significant impedance mismatch between the channel material and the fluid medium, the channel walls serve as nearly perfect reflectors for acoustic waves. Undoubtedly, machining quality of the channels is required high standard. Besides, the width of such a channel is typically a half-wavelength at the excitation frequency, which means that there is a standing-wave with one pressure node in the middle of the channel. For micrometersized particles the excitation is typically in the MHz range and the channel width and height of such devices are both in the order of hundreds of micrometers. This presents a great challenge to the processing of the separator.

Current acoustofluidic separation techniques do not have the throughput needed for apheresis. Currently, the throughput (flow rate) for acoustofluidic separation is 4 μl/min. In order for acoustofluidics to find more clinical relevance, it is important to improve throughput and precision. Dubay et al. reported an acoustic separator utilizing multiple channels to achieve high throughput, entirely made of polystyrene, fabricated by precision five-axis machining, with an average channel width of 544 μm, the throughput of single channel for acoustofluidic separation is about 80 μl/min. Hill from Southampton University in the United Kingdom fabricated an ultrasonic separator based on the principle of one-dimensional standing waves, made of silicon and glass. The depth of the separator using a double-sided alignment process and standard wet KOH etching is 250 ± 40 μm. For the channel made of silicon material, no reports of other fabrication methods have been seen, and the effect of channel quality on ultrasonic separation has not been studied in detail, to our knowledge.

In this work, the effect of channel quality on ultrasonic separation is studied, and the separator processing method based on integrated circuit micro-nano fabrication technology is introduced in detail. The depth dimension of the cavity reaches 200 ± 0.5 μm, and the verticality of the side wall of the cavity reaches 83.36°. The degree of SFPD is less than or equal to 0.25 μm. The separators fabricated in this paper are tested by experiments, which can effectively improve the separation efficiency. Currently, throughput (flow rate) of the acoustofluidic separator is 4 μl/min. The separation throughput (flow rate) in one single cavity in this work can reach to 100 μl/min. This work suggests that if the principle of integrated circuits is further used, multiple separators can be connected in parallel, so that, it is possible to achieve an order of magnitude increase in throughput.

On micrometer scale, the majority of the acoustic methods use a constant frequency to manipulate particles, only a small number of studies have investigated the effect of frequency on the manipulation of the particles. They manipulate particles of different sizes to distribute in different positions (large particles 10 microns, small particles 5 microns) by switching the frequency of the first and third resonant modes of the fluid channel. Sweeping frequency can effectively improve the acoustic radiation force, and almost all the application of frequency-sweep are on centimeter scale. However, the combination of phase difference and frequency sweep to excite the micron-scale separators has not been reported yet, to our knowledge.

This paper proposes to use sawtooth wave frequency sweeping instead of constant frequency (particles are 1–5 micron yeast) to excite the micro-separator, and employ two anti-phase acoustic drivers to suppress multi-mode coexistence in the separation cavity. Experiments prove that the excitation technology can improve the separation efficiency effectively.

**Working mechanism and simulation**

Ultrasonic wave is used as the external field to separate the suspended particles because the acoustic energy in the fluid produces an acoustic radiation force (ARF) on the suspended particles whose sound velocity and density are different from that in the fluid. Under the ultrasonic standing field, the suspended particles will
Acoustic wave in Z-direction, and then the acoustic resonance in Z-direction can be avoided. This team uses two anti-phase PZT-transducers (the phases difference between PZT transducers is) on the bottom to excite the (1, 1) normal mode, and the feasibility has been demonstrated in the previous work.16

Two anti-phase PZT-transducers are attached on the bottom of the separator to excite anti-phase plane wave along x-direction (as shown in Figure 1). If the variation of sound wave after propagating through the matching layer is ignored, the sound source on the plane y = 0 can be written as $q = Q \text{sign}(x - a/2) \exp(j \omega t) \delta(y)$, where $Q$ is the sound amplitude, sign(x) is symbol function ($x < 0$, sign(x) = -1; $x = 0$, sign(x) = 0; $x > 0$, sign(x) = 1); $\delta(y)$ is Dirac function ($\delta(y) = 0$, $y \neq 0$, $\int_0^L \delta(y) dy = 1$); $p$ is the density of the fluid, $c$ is ultrasonic speed, $\omega$ is excitation frequency, $\omega_{1n, n_y} = \pi c \sqrt{(m/x)^2 + (n/y)^2}$ is the two-dimensional normal frequency.

Assuming the inner wall of the fluid cavity to be rigid and resonances in the Z direction to be negligible, the wave equation based on two-dimensional normal mode $(n_x, n_y)$ can be expressed as:\)

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = -\rho c^2 \frac{\partial^2 p}{\partial t^2}$$

(1)

The solution is:

$$p = \sum_{n_x = 0}^{\infty} \sum_{n_y = 0}^{\infty} A_{n_x, n_y} \psi_{n_x, n_y} \exp(j \omega t)$$

$$= \sum_{n_x = 1/4, n_y \neq 0}^{\infty} \sum_{n_y = 1/2, n_y = 0}^{\infty} 2 \rho c^2 Q \cos(n_x \pi / 2) \Lambda_4(o^2 - \omega_{n_x, n_y}^2) \psi_{n_x, n_y} \exp(j \omega t)$$

(2)

It indicates that when $n_x$ is odd number, since the denominator in the coefficient expression will increase with the increase of $A_{n_x, n_y}$, so when $n_x$ is equal to the minimum value of 1, the value of $A_{n_x, n_y}$ reaches the maximum, normal mode $(1, n_y)$ is the easiest one to be exited $(1, 1)$ is selected in this paper.

In this paper, Ansys finite element software is used to support the working mechanism above and the experimental data behind. Assuming that all boundaries of the fluid cavity are rigid condition, and assuming that the sound pressure is uniformly distributed on each inner surface of the fluid cavity. At the bottom of the silicon wafer corresponding to the lateral width of the fluid cavity ($b = 5 \text{ mm}$), two displacements of $1 \mu m$ in opposite directions with a distance of $1 \text{ mm}$ are set to simulate the excitation of two anti-phase acoustic drivers. When the driving frequency is equal to the

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**Figure 1.** Top view and cross-section view of the ultrasonic separator.
resonance frequency of (1, 1) normal mode, the acoustic pressure distribution in the fluid cavity of the separator viewed from the ANSYS analysis results is shown in Figure 2(b). The \( x \) direction is the horizontal direction of the separation chamber, and the \( z \) direction is the flow direction of the fluid. The sound pressure icon from left to right indicates that the sound pressure increases from negative to positive. The green in the middle is close to zero, that is, the sound pressure in the center of Figure 2(b) is close to zero, which is the sound pressure nodal plane corresponding to the position of the standing wave sound pressure nodal plane in Figure 2(a), it indicates that the particles will converge on the plane in the center position in the \( x \) direction. When the first-order standing wave in the longitudinal direction (\( y \) direction) is also excited, the particles will converge into a bunch in the center of the separation chamber and flow out from the middle outlet of the separator. The results are consistent with the theoretical model of the standing acoustic wave formed in the \( X \) direction when the (1, 1) normal mode is excited, as shown in Figure 2(a).

**Discussion**

Based on the working mechanism of (1, 1) normal mode ultrasonic separation, this article discusses the influencing factors of ultrasonic separation efficiency, and summarizes two aspects: the coexistence of multiple modes of the separation cavity, insufficient absolute ARF.

**Coexistence of multiple modes in the cavity**

The cross-sectional width and height of the separation cavity of the ultrasonic separator are \( a = 8 \text{ mm} \) and \( b = 200 \mu \text{m} \), respectively, as shown in Figure 1. The resonant frequency of the two-dimensional \((m, n)\) normal-mode may be expressed as:

\[
f = \frac{v}{2} \sqrt{\left(\frac{m}{b}\right)^2 + \left(\frac{n}{a}\right)^2}
\]

where \( v = 1.48 \times 10^3 \text{ m/s} \) is the propagation speed of sound waves in water. According to formula (3), the resonant frequency of (1, 1) order and the resonant frequencies of other modes close to its resonant frequency are calculated, as shown in Figure 3. According to formula (3), the resonant frequency of (1, 1) order and the resonant frequency of other modes close to its resonant frequency are calculated. As shown in Figure 3, the horizontal axis is the frequency, and the vertical axis is the amplitude of ARF. When the excitation frequency is equal to the normal mode resonance frequency, the ARF in the separation cavity reaches the maximum, which can improve the separation efficiency. If the excitation frequency of the single sound source is equal to (1, 1) resonance frequency 3.701 MHz, the (40, 0) and (2, 1) modes will be excited at the same time, even be (41, 0) and (39, 0). When those different modes are excited simultaneously, the suspended particles in the separation cavity cannot converge in the middle of the \( x \) direction of the separation cavity, which affects the separation efficiency.

**Insufficient acoustic radiation force (ARF)**

ARF is a key factor affecting particle aggregation. The easiest way to improve ARF is to increase the sound pressure by increasing the amplitude of the voltage on
both sides of the piezoelectric transducer. ARF will increase as the sound pressure increases. However, studies have found that excessively high voltage will cause severe energy loss when passing through the piezoelectric layer. Coupled with the resonance of the separation chamber, the temperature of the separation chamber will rise sharply, which will reduce the separation efficiency instead. In severe cases, the separator will be damaged. Laurell et al.\textsuperscript{26} proved through experiments that the method of increasing the voltage does not work and also proved that when the (1, 0) order mode of the separator is excited, the suspended particles cannot converge due to insufficient acoustic radiation force. The time average value of the ARF in the plane standing wave field can be expressed as,

\[
\langle \tilde{F}_{st} \rangle = 4\pi ka^3 (\varepsilon_\infty) K_{st}(\mu, \sigma) \sin(2kx)
\]

where \(\varepsilon_\infty = \rho^* k^2 A^2\) is time-average energy density of a plane standing wave; \(k = \omega/\nu = 2\pi/\lambda = 2\pi f/\nu\) is the wave number. Assuming that the shape change of the particle is ignored and the particle is simplified to a small sphere with radius \(a\), the sound ratio factor can be expressed as:

\[
K_{st}(\mu, \sigma) = \frac{\mu + [2(\mu - 1)/3]}{1 + 2\mu} - \frac{1}{3\mu^2} \quad (5)
\]

Combining equation (4), it can be seen that the ARF amplitude of particles in the fluid is proportional to the third power of the particle radius, proportional to the normal frequency, and inversely proportional to the size of the separation cavity. This means that if the sizes \(a\) and \(b\) of the separator are appropriately reduced, the acoustic radiation force can be increased. The width of the high-throughput separator in this paper \(a = 8\) mm is much larger than the width of the separator in Thomas Laurell’s experiment (width equal to 750 \(\mu\)m). When the mode (1, 1) in this article is excited, the problem of insufficient acoustic radiation force is unavoidable, which is also proved in subsequent experiments.

\textbf{Influence of machining quality of the cavity}

In the working mechanism, the condition of the (1, 1)-order normal mode excited by the double anti-phase PZTs is to assume that the four inner sides of the separation cavity are rigid side walls. The ultrasonic standing wave field in the separating cavity is formed by the superposition of the incident wave and the reflected wave. If the reflection surface of the cavity wall is rough, the incident wave will be diffusely reflected on the wall surface, so that a stable two-dimensional ultrasonic standing wave field cannot be formed; if the inner wall of the separation cavity is smooth and flat, specular reflection can occur, and the stable two-dimensional ultrasonic standing wave field can be formed. High-throughput ultrasonic separation based on the two-dimensional normal mode requires the processing quality of the inner surface of the separation cavity: the high precision of the depth of the separation cavity can ensure that the longitudinal excitation frequency is close to the theoretical value, which is the key factor for exciting the (0, 1) normal mode; the small verticality of the side wall and the bottom surface is conducive to the formation of lateral standing waves; the small flatness of the bottom surface and the side wall is conducive to occur specular reflection.

The ultrasonic separator in this article is composed of silicon and glass. The basic processing technique is to combine the separation cavity etched out of the silicon wafer with glass. Common etching methods include wet etching and dry etching. Common processing methods cannot meet the precision requirements of the separation cavity.

\textbf{Optimization}

\textit{Double acoustic sources excitation model}

In order to solve the problem of the coexistence of multiple modes in the separated cavity when the (1, 1) mode is excited, this paper proposes a double acoustic sources excitation model, as shown in Figure 4. The position design of the acoustic drivers is a key factor for the (1, 1) mode to be excited successfully. Let us assume that the coordinates of the two acoustic drivers are (0, 0) and (c, 0) respectively. The frequencies of the two acoustic drivers are equal. Assuming that the vibration amplitudes in the y direction are equal, the entire vibration process is undamped, the system response is zero, and the fluid in the model is an ideal fluid with no attenuation of sound wave conduction. According to the sound wave interference theory and the wave parameters.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Double acoustic sources excitation model.}
\end{figure}
equation, the surface wave displacement generated by the excitation of two acoustic drivers can be expressed as:

\[
\begin{align*}
  d_{sf1} &= d_{sf0} \cos (kx)e^{j\omega t} \\
  d_{sf2} &= d_{sf0} \cos [(x + c)]e^{j(\omega t + \phi)}. \\
\end{align*}
\]  

(6)

Where \(d_{sf0}\) is the amplitude of the vibration displacement in the \(Y\) direction, \(\phi\) is the phase difference between the two surface waves, and \(\omega\) is the excitation frequency of the acoustic driver.

Superimpose the displacement of the two acoustic drivers to get:

\[
d_{sf} = d_{sf1} + d_{sf2} = \frac{1}{2}d_{sf0}e^{j\omega t}\left\{1 + e^{j(\phi + k_Fc)} + 1 + e^{j(\phi - k_Fc)}\right\}. 
\]  

(7)

If \(1 + e^{j(\phi + k_Fc)}\) and \(1 + e^{j(\phi - k_Fc)}\) in equation (7) are equal and both are real numbers, the vibrating surface will produce standing waves, so we can get:

\[
\begin{align*}
  \phi + k_Fc &= 2P\pi & (P = 0, \pm 1, \pm 2, \pm 3, \ldots) \\
  \phi - k_Fc &= 2Q\pi & (Q = 0, \pm 1, \pm 2, \pm 3, \ldots) \\
  k_Fc &= \frac{T\pi}{M} & (T = 1, 2, 3, \ldots) \\
  M &= T/\eta \\
\end{align*}
\]  

(8)

As shown in Figure 6 set the parameter \(\eta = c/a\), then \(0 \leq \eta \leq 1\); if we choose parameter \(\eta = 1\), it means \(c = a\), the positions of the double acoustic drivers are exactly at the left and right ends of the corresponding bottom of the separation cavity. When the two acoustic drivers are in anti phase \(\phi = \pi\), the normal mode \((M, N)\) in the separated cavity is excited, we can get the displacement of the two acoustic drivers, as shown in equation (9), where \(n\) is an integer greater than or equal to zero.

\[
d_{sf} = \begin{cases} 
  2d_{sf0} \cos(k_Fx)e^{j\omega t} & (M = 2n + 1) \\
  0 & (M = 2n) 
\end{cases} 
\]  

(9)

This article aims to excite the \((1, 1)\) normal mode in the ultrasonic separation cavity. Combining Figure 3, it can be found that the \((40, 0)\) and \((2, 1)\) modes that are closest to the target mode frequency will be suppressed because \(M\) is an even number. And the acoustic displacement of \((1, 1)\) modal excitation is twice that of a single acoustic driver, which means that the acoustic radiation force has also been greatly improved.

**Sawtooth-shaped frequency sweep excitation**

At fixed frequency excitation, particles are concentrated at the stable locations of the acoustic radiation force. Particle translation is achieved by a periodic sweeping of the frequency of excitation, which generates a slowly moving standing wave. Lipkens et al.\(^{27}\) has investigated the effect of the sweep period and the sweep frequency range on particle translation speed, and through experiments proved that the particles velocities are inversely proportional to sweep period and proportional to frequency sweep range. According to Newton's second law, the acoustic radiation force is also proportional to the sweep frequency range and inversely proportional to the sweep period.

The frequency sweep waveform usually has two kinds of sawtooth wave and step wave. Manneberg et al.\(^{28}\) has proved through experiments that sawtooth scanning excitation is more conducive to improve the stability of the lines formed by particle aggregation than single-frequency excitation. Therefore, in this paper, sawtooth wave scanning is used to excite \((1, 1)\) normal mode in the separation cavity. By appropriately increasing the scanning range and reducing the scanning period, the acoustic radiation of the particles can be improved.

**Separator processing method based on micro-nano processing**

In the common micro-nano manufacturing process, the easiest way to make a large-scale separator with a longitudinal depth of 200 \(\mu\)m in the cavity is to use a one-time etching molding technology, and the typical etching technology includes wet etching and dry etching. However, due to the shortcomings of isotropic etching in wet etching, it is difficult for these fabricating methods to simultaneously ensure the flatness of the inner wall, the depth accuracy, and the verticality of the cavity in the separator.

The micro-nano fabrication technology proposed in this paper is based on the semiconductor-based multilayer stack generation and high-precision alignment process, which ensures that the alignment error between the epitaxial patterns of each layer is within 0.3 \(\mu\)m. This effectively avoids vertical errors introduced by lateral etching in deep cavity fabrication.

1. Cavity structural generation

Step 1: Firstly, a SiO2 epitaxial layer with a thickness of about 20 \(\mu\)m is grown on a silicon wafer with a \(<110>\) crystal orientation, and then CMP (Chemical Mechanical Polishing technology) is used to realize the planarization of the wafer surface;

Step 2: Transfer the cavity pattern on the mask to the surface of the oxide layer by positive photoetching, and then remove all the oxide except the cavity area by a wet etching process.

Step 3: Silicon epitaxial 20 \(\mu\)m is grown by chemical vapor deposition method, then CMP is used to realize the planarization of the wafer surface.
Based on the alignment technique of the semiconductor planar-process, the first to third steps are repeated 10 times, and the three-dimensional structure of the separation cavity is designed through such a multilayer film growth technique. This process is shown in Figure 5(a), the yellow area SiO$_2$ in the middle is the separation cavity, the final separation cavity structure is shown in Figure 5(b).

2. Cavity etching and molding

All SiO$_2$ in the cavity area are wet-etched with hydrofluoric acid to form a cavity, as shown in Figure 5(c).

3. Etchback cavity surfaces

Wet etching is used to etchback the all surfaces of the cavity, the alignment error between the various layers of the cavity is eliminated by isotropic etching of hydrofluoric acid and nitric acid, thereby the flatness of the sidewall of the cavity is improved, the final structure is shown in Figure 5(d).

In order to improve the processing quality of the inner wall of the separation chamber, micromachining technology is used in the processing of the separator. Observe the microstructure under a microscope, as shown in Figure 6. The image is very clear, the bottom surface of the cavity is very smooth and flat, and the etched lines of inlet and outlets are regular and clear. The surface finish quality is measured by Dektak 150 stylus profiler, as shown in Figure 7. The depth dimension of the cavity reaches $200 \pm 0.5 \mu m$, and the verticality of the side wall of the cavity reaches 83.36°. The degree of SFPD (Site Focal Plane Deviation) is less than or equal to 0.25 μm. Compared with the common etching method, the processing accuracy has been significantly improved.

**Experiments**

The experimental platform is set up as shown in Figure 8, two ultrasonic transducers are adhered to the left and right ends of the corresponding bottom of the separation cavity through silver conductive adhesive (S05001-AB) with high reflection coefficient, shown in Figure 8(a). Ultrasonic waves passing through the silicon matching layer are transmitted to the channel middle. The transducers are driven by a linear power amplifier.
which is connected to a function generator (33250A, Agilent) with resolution of. A syringe pump is used to supply suspended yeast fluid through the inlet. Finally, the behavior of particles is observed by a microscope camera (A101fc series, German BASLER) through the top layer of Preyx glass. And the captured results of camera can be easily transmitted to the computer with data wire IEEE1394.

The experiments in this article are all based on the separators processed by micromachining technology. Due to the low precision of common etching separators, they usually cannot capture any particle convergence. The normal mode of (1, 1) normal mode is excited by a single acoustic driver and a single resonance frequency, and the experimental results can be captured in repeated experiments, as shown in Figure 9. The Photo of the resonator is taken at time 3 min and 40 s. The particles in the separation cavity converge into lines in the \( X \) direction (i.e. the width direction). After partial magnification, we can calculate that there are exactly 40 lines, which indicates that the (40, 0) mode close to the resonance frequency of the (1, 1) mode is also excited. This experimental phenomenon has also been verified in ANSYS simulation analysis. It is also assumed that all boundaries of the fluid cavity are rigid condition, and assuming that the sound pressure is uniformly distributed on each inner surface of the fluid cavity. At the bottom of the silicon wafer corresponding to the lateral width of the fluid cavity \((b = 5 \text{ mm})\), a displacement of 1 \( \mu \text{m} \) is distributed to simulate the excitation of a single acoustic driver. When the driving frequency is equal to the resonant frequency \((1, 1)\) in the normal mode, the ANSYS analysis results are shown in Figure 10. To make it clearer, the sound pressure distribution of half the size of the fluid cavity of the separator is shown here. In the Figure 10, the standing wave above is set to help illustrate the position of the wave nodal surface in the simulation result below. There are exactly 20 standing wave sound pressure nodes, which means that the particles will converge on the 40 standing wave nodal planes in the \( X \) direction of the separation cavity. This is a good illustration of the experimental results in Figure 9. As analyzed in 2.1, when the separation cavity is excited by a single sound source and a single frequency, there is indeed a problem of multi-mode coexistence in the separation cavity, which is not conducive to the separation of particles.

Combining the above schemes, a sawtooth frequency sweeping method with two anti-phase acoustic drivers is proposed to excite \((1, 1)\) normal mode in the separation cavity. The sweep range is 2 kHz centered at the resonance frequency of \((1, 1)\) mode 3.701 MHz, the sweep period is 1 ms. The PZT-4 transducers are driven by 10 V signals. The top view of the separation cavity taken by the microscope is shown in Figure 11. From the time the suspension was injected into the separation chamber, a large number of particles gathered in the center of the \( X \) direction in less than 10 s, and linear convergence was completely formed within 1 min and 39 s. Compared with the single-frequency single-source
excitation technology, the particle gathering time of this technology is reduced by 2 min, and the particles converge into lines more clearly and stably. This experiment shows that the sawtooth frequency sweeping technology with two anti-phase acoustic drivers improves the response speed and stability of the concentration of suspended particles.

Conclusions

This paper analyzes the excitation technology of (1, 1) mode ultrasonic separation of high-throughput ultrasonic micro-separator. There are two main factors that limit the success of excitation, one is the disorder of the acoustic field caused by the coexistence of multi-modes in the separation cavity, and the other is the lack of absolute acoustic radiation force (ARF), which leads to the inability of the particles to converge. In order to solve these two problems, this paper proposes to use integrated circuit micromachining technology to process the ultrasonic micro-separator, and an excitation method of saw-tooth frequency sweep of two anti-phase acoustic drivers, which can effectively suppress the multi-mode coexistence in the separation cavity and improve the ARF. To excite the (1, 1) mode, the depth dimension of the separator cavity determines the stable excitation of the first-order mode in $X$ direction. Ultrasonic micro-separators based on integrated circuit micromachining technology can reach micro-nano-level processing quality standards. The precise thickness process design of the multilayer film ensures that the depth dimension of the cavity reaches $200 \pm 0.5 \mu m$, and the nano-level high-precision plane alignment process ensures that the verticality of the cavity sidewall reaches $83.36^\circ$. After the cavity is etched and formed, through the etch-back process of the inner wall of the cavity the surface flatness of the cavity sidewall is achieved less than or equal to 0.25 $\mu m$ of the degree of SFPD (Site Focal Plane Deviation). The excitation method of saw-tooth frequency sweep of two anti-phase acoustic drivers replaces single driver with single frequency, which not only effectively suppresses the multi-mode coexistence in the separation cavity, but also improves the (ARF) and shortens the time for the pattern formation of particle convergence. Based on the interdisciplinary theoretical analysis, this paper proposes the fabrication method of the micro-separator and the excitation method of saw-tooth frequency sweep of two anti-phase acoustic drivers, which provides the research foundation and reference value for the practical applications of acoustic separation.

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