Progress in Ultrasonic Nano Manipulations

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Abstract—Ultrasonic nano manipulation is an emerging technology, which has great potential applications in the assembly, measurement and fabrication of nano materials, handling of biological samples, manufacturing of nano sensors, new material syntheses, etc. In recent three years, the authors’ research team proposed and developed a series ultrasonic manipulators with the functions such as nano trapping and transfer, nano rotary driving, and nano concentration. Controlled acoustic streaming eddies are used in the nano manipulations. Compared with other nano manipulation techniques, they have the features such as very low temperature rise at the manipulation area, little selectivity to manipulated samples, being implemented on the substrates given by customers, etc. This paper reports our latest progress in the function enhancement of ultrasonic nano manipulations, simulation of the acoustic streaming employed, and modeling of the ultrasonic devices.

Keywords—Nano manipulation, Acoustic streaming, Ultrasonic device.

1. INTRODUCTION

With the development of biomedicine, micro/nano fabrication, new material and so on, devices for actuating nano materials are being required [1, 2]. Required actuation functions for nano materials include trapping, positioning, transfer, release, revolution, removal, concentration, assembly, sorting, etc. These functions are also called nano manipulation. However, most of the above listed nano manipulation functions cannot be effectively and efficiently realized by the conventional actuation technology, which have limited driving forms and operating principles [2]. To fulfill the demands, lots of strategies have been proposed and investigated. They can be classified as optical [1, 3], magnetic [4], electric [5], mechanical [6], AFM [7], microfluidic [8] and acoustic methods [9-15], based on the physical principles which they use.

Ultrasonic nano manipulations utilize the sound induced flow or acoustic streaming to manipulate nanoscale materials. In recent three years, the authors’ work proposed and realized a series of nano manipulations by the means of controlled acoustic streaming. They include trapping, orientation, positioning, transfer and rotation of individual nanowires in deionized water, and concentration of nanowires and nanoparticles in deionized water [2, 9-13]. It has the features such as little selectivity to the material properties of manipulated samples, little heat damage to manipulated samples, diverse manipulation functions, and no need to dispose MEMS or NEMS structures on the substrate. Although it has very large potential applications in the fields such as biomedicine, micro/nano fabrication, material engineering, renewable energy, etc., researches on the principle, structure design, and application of these devices are still superficial and insufficient [2]. Actually there were few reports on the ultrasonic manipulations of a single nano object before the authors’ work. This paper reports our latest progress in the function enhancement of ultrasonic nano manipulations, simulation of the acoustic streaming employed, and modeling of the ultrasonic devices.

II. INTEGRATION OF NONCONTACT AND CONTACT TRAPPING FUNCTIONS INTO ONE DEVICE

In ultrasonic nano trapping, there are two working modes, i.e., the noncontact and contact modes. The noncontact trapping mode enables the device to handle sticky nano samples, and the contact trapping mode makes the transfer of a trapped sample convenient. However, the existing technology cannot integrate the noncontact and contact nano trapping functions into one device [9, 12].

Fig. 1 shows the experimental setup to implement the noncontact and contact-type trapping of individual nanowires by one device. The device is simply made up of the piezoelectric plate, vibration transmission needle (VTN) made of steel, and micro manipulating probe (MMP) made of fiberglass. The VTN is bonded along the narrow side of the piezoelectric plate. The MMP is bonded to the VTN’s tip, and parallel to the piezoelectric plate. The resonance frequency of the device is about 136 kHz, at which the VTN vibrates flexurally. In the frequency range from 131.2 ~ 132.2 kHz, the trapped nanowire is not in contact with the MMP, and it is in contact with the MMP in the frequency range from 133.9 ~ 134 kHz. Figs. 2 and 3 contain a series of images to show the noncontact and contact trapping and transfer of a silver nanowire, respectively. In both modes, the AgNW rotates while being sucked to the MMP. From image b to d in Fig. 2, the trapped nanowire is moved on the substrate surface by moving the manipulating device. From image d to g in Fig. 3, the trapped wire is moved above the substrate surface, and in image h in Fig. 3, the trapped nano wire is released.
Fig. 1 Experimental setup for the noncontact and contact-type trapping of a single silver nanowire. (a) Schematic diagram. (b) Construction of the ultrasonic transducer.

The noncontact and contact trapping modes are realized by employing different acoustic streaming field patterns around the micro manipulating probe. Our calculation shows that the difference in acoustic streaming fields in the noncontact and contact modes, is caused by the change of the phase difference among the normal vibration components at the root of the micro manipulating probe.

Fig. 2 Noncontact trapping of a single AgNW by the MMP’s tip in water film.

Fig. 3 Contact trapping of a single AgNW by the MMP’s tip in water film.

Our experiments show that the noncontact mode has a working frequency band width of 1 kHz, while the contact mode has a working frequency band width of only 0.1 kHz. Increasing the working frequency band width for the contact mode remains a challenge.

III. ACOUSTIC STREAMING

At the present stage, acoustic streaming is the only means employed in the ultrasonic nano manipulations [2]. For better and wider applications of acoustic streaming in nano manipulation, more convenient and efficient numerical methods are needed to calculate the acoustic streaming field in the devices and to analyze its change with the working and structural parameters of devices [16]. We proposed and developed a numerical method, which can make use of the COMSOL Multiphysics finite element method (FEM) software to effectively simulate the acoustic streaming. Furthermore, based on the simulation results, effective methods for controlling the acoustic streaming fields in nano manipulations have been achieved.

The computation process consists of three steps [16]. In the first step, the sound field is solved with the multiphysics coupling modules of the software. In the second step, vibration velocity and sound pressure of the sound field are used to calculate spatial gradients of the Reynolds stress and mean pressure, which generate the acoustic streaming, by the post processing functions of the software. In the last step, the steady acoustic streaming is solved by the fluidic dynamics module, with proper boundary conditions for the acoustic streaming. The steady acoustic streaming satisfies the following equation:

\[ \rho_0 \left( \bar{\nabla} \cdot \bar{\vec{u}} \right) = F_j - \bar{\nabla} \cdot \bar{p}_2 + \eta \bar{V}^2 \bar{u}_j \]  

(1)

where \( \bar{u}_j \) is acoustic streaming velocity, repeated suffix \( i \) and \( j \) represent \( x, y \) and \( z \) in a 3D model, \( \rho_0 \) is the medium density in the undisturbed state, \( F_j \) is the gradient of the Reynolds stress which acts on the fluid as a driving force of the acoustic streaming, and \( \bar{p}_2 \) is the time average of the 2nd order pressure or mean pressure. \( F_j \) is calculated by

\[ F_j = -\bar{\nabla} \left( \bar{\rho}_j \bar{u}_j \right) / \partial x_i \]  

(2)

where \( u_j \) is vibration velocities in the sound wave, and the bar signifies the mean value over one period. \( \bar{p}_2 \) is calculated by

\[ \bar{p}_2 = \frac{1}{2 \rho_1 c_0} \frac{B}{A} \left( \langle p_i^2 \rangle \right) \]  

(3)

where \( p_1 \) represents the (1st order) sound pressure, \(< >\) represents the time average over one time period, \( c_0 \) is the medium sound speed in the undisturbed state, and \( \frac{B}{A} \) is the nonlinear parameter of the medium. The acoustic streaming also satisfies the continuity equation

\[ \rho_0 \bar{\nabla} \cdot \bar{\vec{u}}_j / \partial x_i = 0 \]  

(4)

Fig. 4(a) shows the contact type trapping process of a AgNW on the surface of a silicon substrate in deionized water film, reported in Ref. 9, and Fig. 4(b) is the calculated acoustic streaming field on the silicon substrate surface and in the \( yz \) vibration plane. At the root of the micro manipulation probe (the excited part), there are three orthogonal vibration components, which have different amplitudes and initial phases. According to our calculation, the acoustic streaming pattern is dependent on the phase differences and vibration amplitudes of these three orthogonal components. To generate
a useful acoustic streaming field for the contact type trapping of a nanowire, the phase difference between the $y$ (or $x$) and $z$ vibration components must be close to $\pm 90^\circ$, and the amplitude of the $x$ (or $y$) vibration component must be small enough compared to the other vibration components.

Also, a droplet-ultrasonic stage system, in which a micro droplet located at the center of the ultrasonic stage is used to concentrate nanoscale material [10], is modeled and analyzed by the FEM, as shown in Fig. 5. The computed acoustic streaming field, shown in Fig. 5, can well explain the nano concentration phenomenon in the droplet-ultrasonic stage system, and useful guidelines for enhancing the concentration capability without sacrificing the manipulation stability are also obtained.

### IV. DEVICE MODELING

Controlled rotary driving of single nano objects is an important technology in the assembling of nano structures, handling of biological samples, nano measurement, etc [2]. However, there have been little analyses on the ultrasonic transducers for the ultrasonic nano rotary driving [13], which makes the transducer’s optimization impossible. Recently, the vibration characteristics of the ultrasonic transducer for rotary driving of single nanowires (NWs), which has been proposed by the authors’ group, have been analyzed by the 3D finite element method (FEM), and some useful guidelines for designing the transducer are achieved.

Fig. 6 shows the structure and size of the vibration excitation system. The ANSYS software is used in the FEM analyses. A 3D FEM model of the device is shown in Fig. 7. The solid5 elements are used for the ceramics and the solid45 elements elsewhere; A constant damping ratio and the Full Method solver are used for the harmonic response calculation.
The phase of the Y-directional vibration displacement minus that of the Z-directional vibration displacement at point O is defined as \( \Delta \phi \). Fig. 8 shows the computed \( \Delta \phi \) versus driving frequency. It is seen that there exist some frequencies at which \( \Delta \phi = \pm 90^\circ \), which means that the resultant of the Y- and Z-directional vibration components of the micro manipulating probe (MMP) is an elliptical motion at these frequencies. Thus at these driving frequencies, eddies can be generated around the MMP, which can drive the NWs to rotate. This well explains the experimental phenomenon reported in our previous work [13]. Moreover, based on the order of magnitude, it is known that point A corresponds to the working point in the experiments. Fig. 9 shows the computed vibration displacement at the MMP’s tip versus the MMP’s length \( L_m \). It is seen that at 137 kHz, the MMP with a length \( L_m \) of 1.42 mm resonates. To ensure the performance consistency of the device, the MMP’s length \( L_m \) or the driving frequency should be designed to avoid the resonance of the MMP. In addition, it is found that the working point can still exist when the commonly used metal materials in ultrasonic transducers, such as steel, copper and aluminium, are used as the vibration transmission strip, and may become unstable or disappears when the vibration transmission strip’s length, width and height changes.

**Fig. 8** Computed phase difference \( \Delta \phi \) versus driving frequency.

**Fig. 9** Computed vibration displacement at the MMP’s tip versus the MMP’s length \( L_m \).

### V. SUMMARY

The experimental and theoretical work has demonstrated that acoustic streaming can be used as an effective physical means for nano manipulations, and it can be effectively controlled by the phase difference between the normal vibration components of the micro manipulating probe. The noncontact and contact trapping functions can be integrated in one device by utilizing two different acoustic streaming fields generated at different working frequencies. Vibration control of the ultrasonic manipulators is critical to realize or enhance a nano manipulation function. As an emerging actuating technology, the ultrasonic nano manipulation is facing lots of technological challenges such as the diversification of manipulation functions and manipulated samples, enhancement of manipulation functions, device vibration control, etc.

### REFERENCES


actuators, piezoelectric transducers and transformers, physical effects of ultrasound, wireless drive of piezoelectric components, energy harvesting from oscillation, and other novel utilization of vibration. He is a senior member of IEEE, and the Editorial Board Member of three international journals. Dr. Hu won the Paper Prize from the Institute of Electronics, Information and Communication Engineers (Japan) as the first author in 1998, and was awarded the title of valued reviewer of Sensors and Actuators A: Physical and Ultrasonics. He has given eight invited talks at international conferences, and is the honorary chairman of IWPMA 2011, held in USA. He is the author and co-author of more than 200 papers and disclosed patents, including more than 70 full papers published in SCI journals, and his research work in ultrasonic micro/nano manipulations has been highlighted by 7 international scientific media. He is also the author of monograph book “Ultrasonic Micro/Nano Manipulations” (2014, World Scientific, Singapore).