DISPLACEMENT OF DROPLETS ON A SURFACE USING ULTRASONIC VIBRATION

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Abstract

Liquids handling is an important issue in biomedical analysis. We propose two different devices for ultrasonic droplets displacement. Each one involve a different physical phenomenon. The first device proposed is a low frequency standing waves using flexural plate waves (FPW). In this case, acoustic radiation pressure is involved for the displacement. The second one uses high frequency travelling waves: Surface Acoustic Waves (SAW). The droplet is moved thanks to acoustic streaming. Some theoretical and experimental results are presented .

Introduction

The study of the interaction between a vibrating surface and a liquid led us towards the design of a new method of handling of small quantities of liquid. We propose two different devices to move small droplets that emphasize the interaction between liquid and on the one hand FPW and on the other hand SAW.

The first device is a metallic beam with two stacks of multi-layers piezoelectric actuators on each end. When a standing wave is generated with sufficiently high vibration amplitude, it has been observed that a droplet moves towards the nearest anti-node. A theoretical explanation of the phenomenon has been performed . For each flexural mode, the position of the antinodes is fixed by the boundary conditions. So if different flexural modes are excited we obtain different equilibrium positions. Consequently, we achieve to move the droplet by switching the excitation frequency of the beam. With the second device Rayleigh waves are generated by inter-digital transducers (IDT) of aluminium deposited on a $LiNbO_3$ layer. The Rayleigh wavelength is about 100µm at 80 MHz. The surface acoustic waves are propagating on the surface and absorbed by the droplet. The motion effect is caused by the acoustic streaming . The fluid is intended to be pushed away from IDT. We can move the droplet in two dimensions by laying out several IDTs all around the desired surface of displacement.

Effect of acoustic radiation pressure

He very first interest of effect of acoustic radiation pressure has came from experimental experimentations. When one spreads a liquid layer on a plate, the free surface of the liquid is plane. If FPW of the plate is excited, a permanent deformation of the liquid surface can be observed as one can see on figure 1.

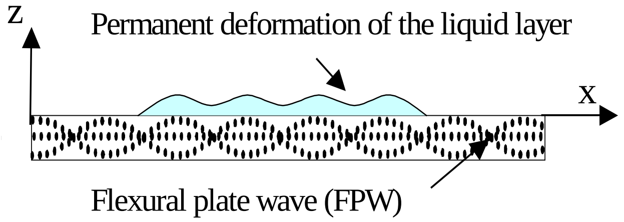

Figure 1: Experimental observations on acoustic radiation pressure effect on a liquid layer.

A better understanding of the origin of the permanent deformation of the liquid layer has been proposed by studying the equilibrium of the surface when the FPW are excited.

The forces take into account for the equilibrium of the liquid surface are:

- The hydrostatic pressure: $P_h = -\rho g z$
- The capillary forces: $P_2 - P_1 = \sigma\left(\frac{1}{R_x}+\frac{1}{R_y}\right)$
- The acoustic radiation pressure:

$$P_r(x) = \rho c^2 \left(\frac{2+\frac{B}{A}}{2}\right)\left\langle\left(\frac{\partial u(x)}{\partial x}\right)^2\right\rangle$$

The acoustic radiation pressure expression given above is a time independent second order term in the expression of acoustic pressure. The terms A and B are non-linear effect constants, $u(x)$ is the sound displacement , ρ is the liquid density, σ is the liquid surface tension and c is the sound velocity in the liquid, R_x and R_y the radius of curvature. Measurements of vibrating plate displacement and liquid surface deformation has been performed [1]. The comparison between analytical and experimental results are not so bad. In the two cases, 1 µm displacement gives 1mm deformation of the liquid surface.

The acoustic streaming has also been evaluated. The acoustic streaming pressure (P_{as}) can be written with approximation as: $P_{as} \le \frac{1}{2}\frac{z_0}{l_\mu} P_r$ where z_0 is the water thickness and l_μ is the absorption length given by: $l_\mu = A\left(\frac{f}{f_1}\right)^{-2}$ with A is a constant for a given liquid and $f_1 = 1\text{MHz}$ [2]. The numerical application gives: $P_{as} \le 10^{-6} P_r$ for $f = 30kHz$. As a result, the effect of acoustic streaming is negligible at such low frequencies.

These experimental observations and analytical calculations led us to imagine that the force created by the acoustic radiation pressure might make move a single droplet.[3] If FPW vibration amplitude is high enough, a droplet deposited on a beam moves toward the nearest anti-node of the FPW, i.e the maximum of radiation pressure, as shown on figure 2.

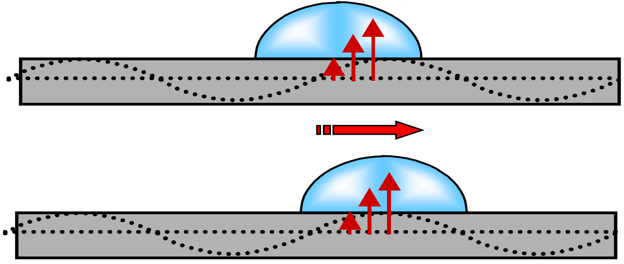

Figure 2 : Principle of a droplet displacement.

So, as a result, one has to change the anti-node position to move the droplet. As the boundary conditions of the beam determined the position of the anti-node of each flexural mode, several modes have to be successively excited to perform the displacement. The frequencies of high order flexural modes of a beam have been evaluated by a finite element analysis. This study gave us the frequency and the anti-nodes position for each mode to establish the sequence of modes to use to get a good displacement.

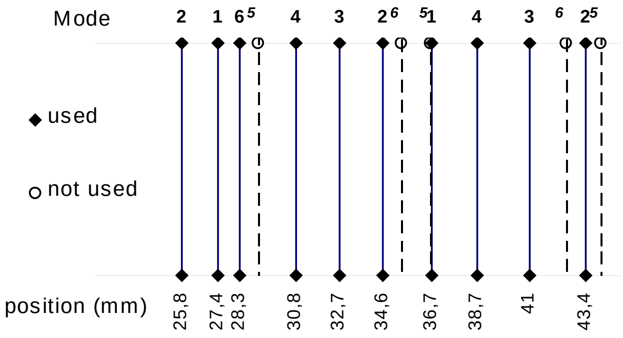

Figure 3 : Position of used modes on a part of the beam.

Mode rank	Frequency (Hz)	Mode number
16	22986	1
17	25365	2
18	27751	3
19	30223	4
20	32705	5
21	35112	6

Table 1 : Frequencies and ranks of flexural modes used for dispalcement. Mode number is a arbitrary number.

An geometric optimisation of the beam has also been performed. We designed a periodical beam to reject disturbing modes frequency at a higher level. In that case a bad-gap in frequency is achieved for non-desired modes without disturbing flexural modes frequency as it is shown on figures 4 and 5.

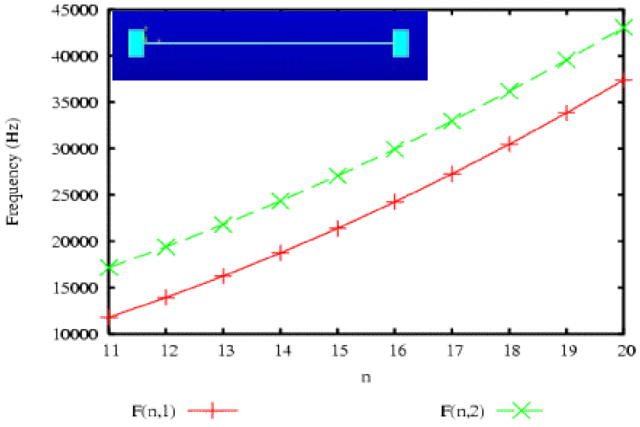

Figure 4: Frequency of flexural (n,1) and disturbing (n,2) modes for a classical beam.

The number of nodes along the length is given by the first number and along the width by the second number.

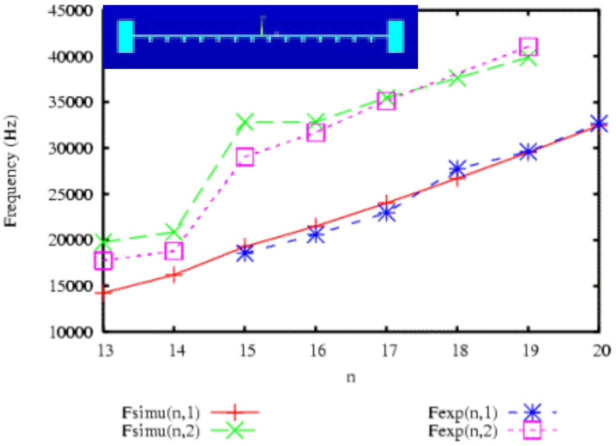

Figure 5 : Calculated and experimental frequency of flexural (n,1) and disturbing (n,2) modes for a periodic beam.

Experiments have shown that the elimination of disturbing modes is quiet efficient, and that a step by step displacement of a droplet can be performed by switching the excitation frequency of FPW.

Effect of acoustic streaming.

The second device involves a different physical phenomenon. Travelling waves are generated from Inter Digital Transducers (IDT) deposited on a piezoelectric medium. The SAW are propagating on the surface and absorbed by the liquid drop. The energy absorbed by the droplet make it move in the direction of wave propagation as it can be noticed on figure 6:

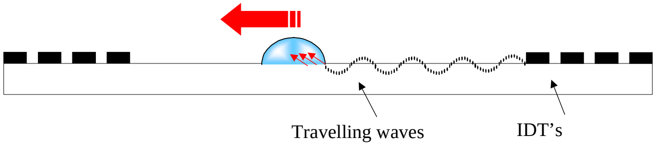

Figure 6

For the realisation of the device, aluminium is sputtered on a 3 inches $LiNO_3$ wafer. The (YX)/128° cut has been chosen because it has a good coupling coefficient and low losses in the bulk. The thickness of the substrate is 500µm. The IDT have 100µm period, 25 µm witness. 25 SAW delay lines have been built along each direction, respectively operating at 73 and 79 MHz. Each delay line is composed of two IDT separated by a distance of more than two inches. The accessible surface was then homogeneously prepared to promote an hydrophobic behaviour in order to favour the droplet displacement as it is shown on figure 7.

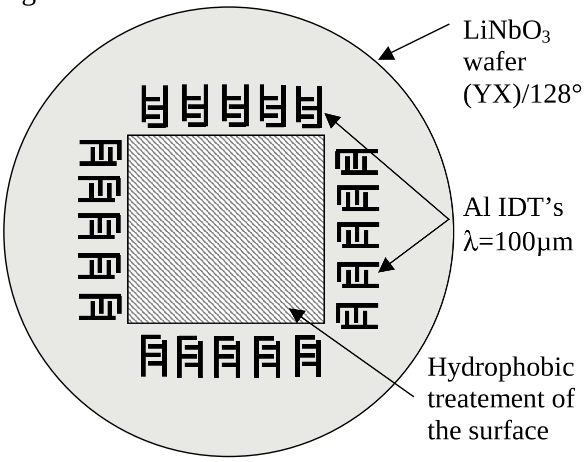

Figure 7: Diagram of the SAW displacement device.

With such a design, 2D displacement can be performed. The position of the droplet can also be detected in the perpendicular direction of the displacement by emitting a signal in an IDT and analysing the response on the opposite IDT (see figure 8). If the droplet is moving in the $\vec{x}$ direction, the IDT lines in the $\vec{y}$ direction are used for real time detection of drop localisation. When the drop has reached the desired x coordinate, the $\vec{y}$ oriented IDT lines become displacement lines and the $\vec{x}$ oriented IDT lines become detection ones.

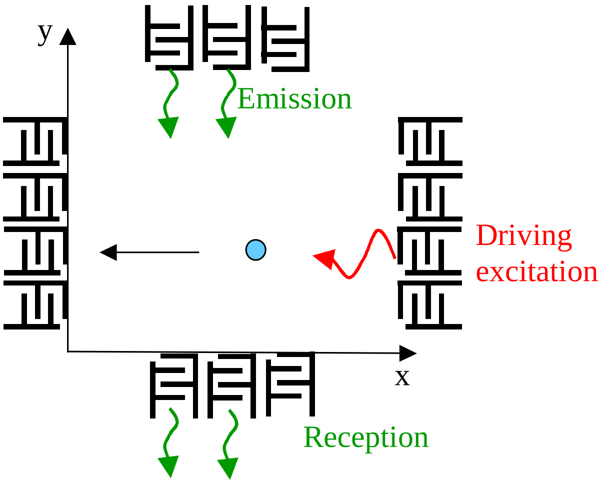

Figure 8: Diagram of droplet displacement and detection with the SAW device

The position of the droplet can be determined in real time as well as its velocity. Experiments using intermittent drive have been performed. The droplet has a step by step movement. It can be localised even if it is in front of one line of detection. As it is shown on figure 9, the droplet position can evaluated with sufficient accuracy. This figure represents the transmission response on one detection line. The acoustic vibration beam is roughly 2mm wide all along the displacement area thanks to a low beam steering.

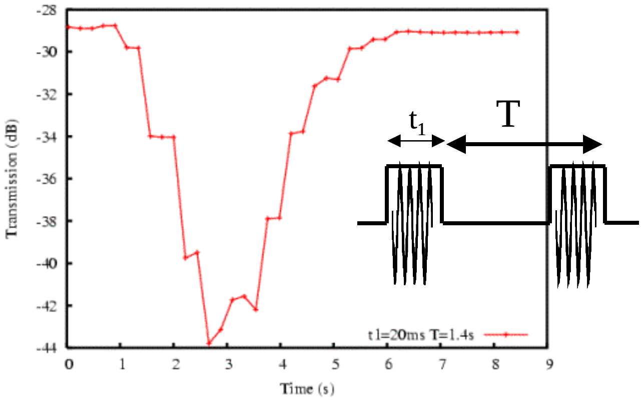

Figure 9 : Transfer function of a delay line when a droplet crosses it (intermittent drive)

To determine the velocity of the drop, continuous drive may be used to provide from errors due to drop acceleration. As one can see on figure 10, the measurement of time that the droplet crosses the detection line gives the velocity knowing the detection line width. The dependence of droplet velocity with input power can be deduced.

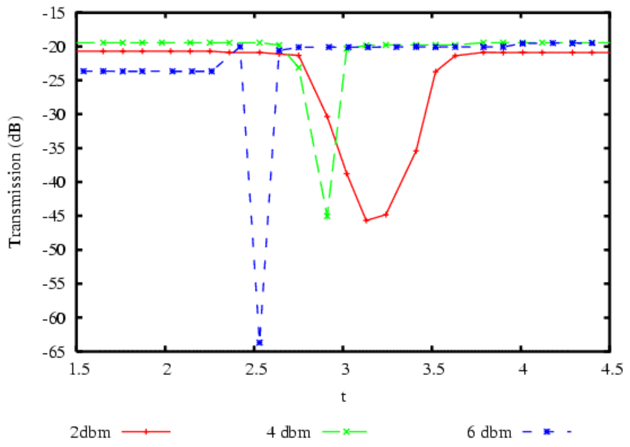

Figure 10 : Transfer function of a delay line when a droplet crosses it (continuous drive) for different power of driving excitation

Conclusions

Two different devices for biomedical or biochemical analysis have been performed. With the first one, acoustic radiation pressure is studied theoretically. Only a step by step displacement has been performed but this device has the advantage to be composed of cheap materials and to have low frequency working. The other device offers continuous or step by step in-time controlled movement but it must be fabricated with a piezoelectric material. The cost can be reduced by deposition of ZnO on silicon wafer for example.

References

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