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Modelling a surface acoustic wave based remotely actuated microvalve

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Abstract

We present a normally closed, remotely actuated, secure coded, electrostatically driven active microvalve using passive components. This is carried out by utilizing the complex signal processing capabilities of two identical 5 × 2-bit Barker sequence encoded acoustic wave correlators. An electrostatically driven microchannel, comprising two conducting diaphragms as the top and bottom walls, is placed in between the compressor interdigital transducers of the two correlators. Secure interrogability of the microvalve is demonstrated by finite element modelling of the complete structure and the quantitative deduction of the code dependent microchannel actuation. Furthermore, the influence of the excited acoustic modes of the correlator on the microchannel deflection is investigated to optimize the microvalve design.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

With the ever increasing demand for high-performance microfluidic devices and the continuous quest for miniaturization, the development of novel and innovative microvalves has witnessed rapid growth in recent times. Most of the research in this area is focused on improving the performance of the microvalve by targeting features such as flow rate, leakage flow, power consumption, response time and disposability [1, 2]. However, the constant expansion of the domain of application of these devices into fields as diverse as life sciences and chemistry is placing new demands on the existing models. One among these new design requirements is the remote interrogability of the microfluidic device. The capability to wirelessly control fluid flow can emerge as an attractive technology enabling various biomedical applications. Furthermore, most of the existing microfluidic devices in biomedical implants are either battery powered or have external pump modules that are connected to the patient by means of a passive port [3, 4]. The use of a battery would place additional constraints on the device size and would require an electronic circuitry module. Hence, the development of an active microvalve with fully passive components, enabling wireless control of fluid flows, is a key task in the realization of compact high performance biomedical implants. Moreover, such a device would provide a freely programmable, time-modulated control profile to ensure patient safety and comfort in long-term treatment.

Microfluidic devices using acoustic streaming have been investigated in the past [5, 6]. These devices use surface acoustic waves or flexural plate waves to cause fluid motion, through hydrodynamic coupling, on the planar surface of the piezoelectric material. Acoustic streaming based microfluidic devices have several advantages, such as low fluidic impedance of the channel, a simple structure and low sensitivity to the electrical and chemical properties of the fluid. However, secure actuation of wireless devices using acoustic streaming is limited only to frequency addressability rather than discrete code addressability, thus rendering them inefficient for remote interrogation applications. This shortcoming is tackled, in this paper, by using two identical 5 × 2-bit Barker sequence encoded surface acoustic wave (SAW) correlators placed one on top of the other with an air gap and suspending an edge-clamped microchannel with two conducting diaphragms between the compressor interdigital transducers (IDTs) of the correlators. The correlator's response is employed to impart ultrasonic energy on the conducting diaphragms using electrostatic actuation. Thus we combine the high frequency operation of the ultrasonic, secure code embedded, acoustic correlator with low power, a fast response time, and reliability of electrostatic actuation. Successful wireless operation of this

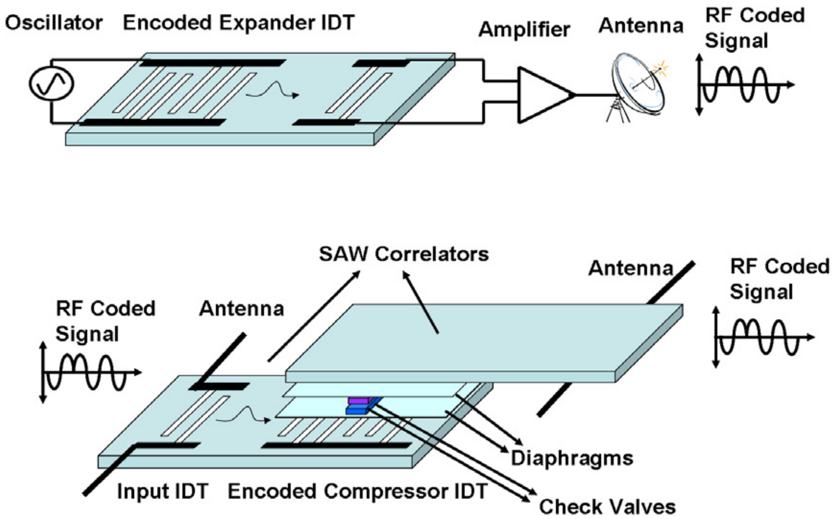

Figure 1. Wireless microvalve transmitter–receiver configuration.

device hinges on the precise occurrence of fluid flow when interrogated by a correlating binary phase-shift keying (BPSK) signal. The microvalve is normally closed and is opened by using the deformation of the diaphragms caused by the electrostatic effect. The risk of high leakage and valve clogging is addressed by employing both diffuser elements and check valves in the structure.

To facilitate optimal design of microelectromechanical systems (MEMS) devices based on such microactuators, efficient simulation schemes for analysing the channel deformation are required. The physical behaviour of microcomponents is best described by partial differential equations, which are typically solved by finite element methods. Due to the complexity involved in combining the electro-acoustic and electrostatic mechanisms, a systematic design and optimization of the active microvalve is best achieved with finite element method (FEM) modelling. Furthermore, coupled field simulations are vital for capturing both electro-acoustic and electrostatic–structural interactions in a single finite element run and for taking into account non-linear effects that are inherent in MEMS devices. Hence, in this work, we model the whole structure by employing a direct FEM to verify the functionality of the concept. The FEM simulation architecture for the structural components of the microvalve consists of two major subsystems: a SAW correlator electro-acoustic analysis, including the voltage response and the influence of the excited acoustic modes, and a microchannel electrostatic analysis that captures the channel deformation and the code dependent behaviour of the structure.

In this paper, the FEM modelling and simulation of a two-dimensional, remotely interrogatable, active microvalve is presented using two 5×2-bit Barker sequence encoded SAW correlators. In section 2 we discuss briefly the principle of operation, the transmitter–receiver architecture and the ON–OFF operation of the microvalve structure. Then, in section 3, we present the SAW correlator design, where the dimensions of the structure and materials are discussed. The simulation results comprising the admittance, output voltage response graphs in the frequency domain are outlined in the same section. In section 4, we present the microchannel electrostatic model design and the simulation results with diaphragm deflection analysis for variable acoustic modes and different input interrogating code sequences.

2. Principle of operation

The design of our novel, passive, wireless microvalve is motivated by the aim of high-resolution volumetric dosing and the demand for a minimum device size and power consumption. The core components of the microvalve are two identical SAW correlators, two diaphragms and an antenna array. The diaphragms are suspended with an air gap between the compressor IDTs of the correlators forming a microfluidic channel. The resulting correlated output at the compressor IDT of the correlator generates an electrostatic field within the air gap which in turn deflects the diaphragms, thereby regulating fluid flow through the microfluidic channel.

The wireless telemetry system for the SAW based microvalve is depicted in figure 1. By means of the antennas, the microvalve captures part of the electromagnetic energy to provide power for its own operation. One of the advantages of this approach is the ability to establish bidirectional communication between the microvalve and the interrogator. Moreover, this concept does not allow simultaneous triggering of several microvalves present in the same electromagnetic field as each device is encoded with a different code. System level protocols, such as those in use in contactless smart-card readers, allows a single controller to communicate with several individually identified microvalve.

A coded SAW based communication system for the microvalve consists of an expander IDT in the transmitter and a compressor IDT in the receiver, as shown in figure 1. A narrow pulse or a sinusoidal waveform is fed to the expander IDT to generate a coded acoustic signal depending on the geometry of the expander IDT. These acoustic waves propagate through the substrate to the transmitting IDT, which transforms these coded

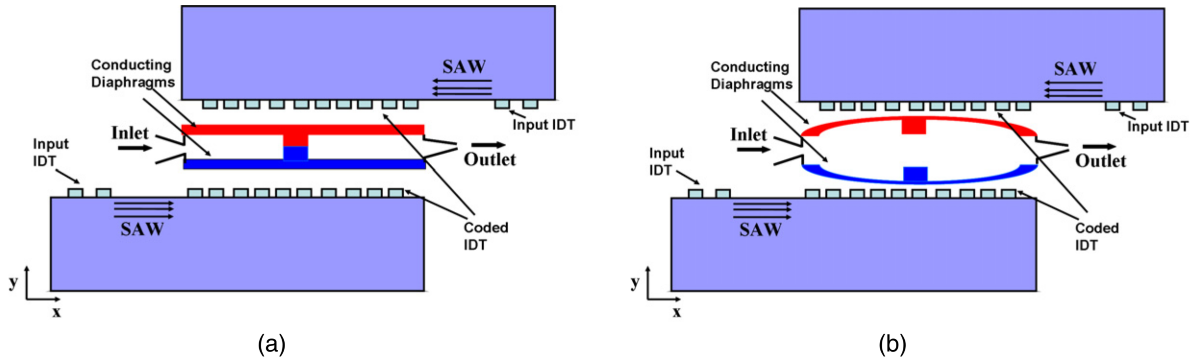

Figure 2. Microvalve in (a) the OFF/normally closed state and (b) the ON state.

acoustic waves to an electrical coded RF signal. The output from the transmitting IDT is fed to an amplifier, to strengthen the signal, and then to a transmitting antenna. The receiver consists of two identical correlators, the operation of which is explained in section 3, with their input IDTs connected to the receiving antennas to intercept the transmitted coded RF signal. The expander in the transmitter is an exact replica of the compressor/coded IDT of the correlators. The coding of the expander and compressor determines the autocorrelation function performed by the correlators. The resultant response of the acoustic devices is then electrostatically coupled to the conducting diaphragms, suspended between the compressor IDTs with an air gap. Thus the actuation method not only depends on the excitation frequency but also on the code of the transmitted BPSK signal. The microchannel comprises two diaphragms with check valves and an inlet and outlet diffuser element on either side of the channel. Apart from the fluid flow resistance of the inlet and outlet diffuser elements, the leakage is further controlled by the check valves. When an electrostatic force is applied, the diaphragms are pulled towards the compressor IDT of the correlators causing the check valves to separate. Thus, the simultaneous actuation of the diaphragms at ultrasonic frequencies by the correlating input signal allows the microvalve to induct and expel fluid through the check valves in the channel.

The valve efficiency is a critical parameter for microvalves used in ON–OFF switching applications. The valve efficiency of an active microvalve with diffuser elements is poor in the reverse direction due to high leakage. The desired leak-tight operation makes it necessary to incorporate microcheck valves on the diaphragms in the fluid channel. The lateral dimensions of the check valves are designed to make them stiff enough to resist bowing under pressurization caused by the fluid in the idle state and yet compliant enough to allow for diaphragm motion during actuation. The sketches in figure 2 depict the functionality of the microvalve in the OFF/normally closed state and the ON state. In the OFF state the check valves push tightly against each other as shown in figure 2(a). Assuming a perfect check valve, the fluid flow through the channel is shut-off in the OFF state or even when there is a mismatch in the operating frequency and code of the interrogating BPSK signal. In the ON state, when interrogated by a correlating signal the double membranes inflate due to electrostatic actuation and inhale the fluid into the chamber. Since this is happening at ultrasonic frequency the expansion and compression of the channel volume allow the compressed fluid to escape through the outlet.

The microchannel dimensions and the diaphragm deflection depend on the application envisaged for the device. The piezoelectric material's electromechanical coupling capabilities, the encoded code of the SAW correlator, the diaphragm material and thickness, the air gap, the compliances of the fluid and check valve elements in the channel, and the nature of the interrogating RF signal all contribute to the performance of the microvalve device. The current research primarily focuses on the modelling and optimization of this novel microfluidic structure with emphasis on secure actuation caused by combining electro-acoustic and electrostatic mechanisms. The modelling is carried out using finite element analysis. Both aspects are explained in detail in the subsequent sections.

3. SAW correlation

The need to optimize and verify individual components of the device in order to achieve the desired performance of the integrated assembled system is clearly evident. Hence, we take the approach of modelling and optimizing a SAW correlator first and then proceed to analysing the electrostatic actuation of the microchannel caused by the correlators.

A brief description of the correlator operation is provided here for the sake of clarity. A SAW correlator, as shown in figure 3, is a passive pulse compression filter that operates through the correlation of phase shifts in the transmitted RF signal. It consists of an input IDT and a coded output IDT deposited on top of a piezoelectric substrate. The input IDT transduces the coded input RF signal into an acoustic wave. The electrodes of the output IDT are phase coded during construction in such a way that the correlator converts the correctly phase coded acoustic wave to a RF modulated electrical pulse. The device will respond with a correlation peak only when the code of the interrogating RF pulse matches with the embedded code in the output IDT, thus enhancing the processing gain of the correlator by combining the code reception scheme with the high-Q operation of a bandpass filter [7]. For all other transmitted signals with different codes, even those excited at the same frequency, the correlator

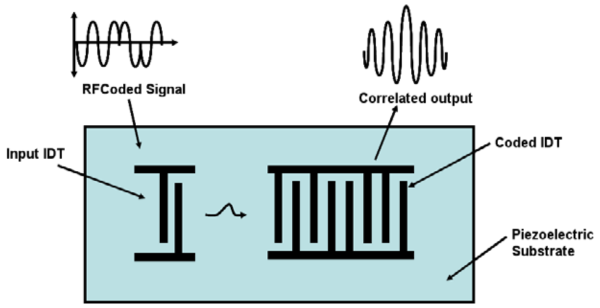

Figure 3. Surface acoustic wave correlator.

would respond with a pseudo-random noise. The preferred coding scheme is a combined Barker sequence due to the high processing gain.

3.1. Geometry

The modelling of SAW devices is mathematically equivalent to the resolution of the partial differential equations of piezoelectricity [8] in equation (1) and (2) defining the amplitudes of the mechanical displacement u_i and the electrical scalar potential ϕ:

$$c^E_{ijkl}\frac{\partial^2 u_k}{\partial x_j \partial x_l} + e_{kij}\frac{\partial^2 \phi}{\partial x_k \partial x_j} = \rho\frac{\partial^2 u_i}{\partial t^2} \tag{1}$$

$$e_{ikl}\frac{\partial^2 u_k}{\partial x_i \partial x_l} - \varepsilon^S_{ik}\frac{\partial^2 \phi}{\partial x_i \partial x_k} = 0 \tag{2}$$

where e_{kij} is the piezoelectric constant, ε^S_{ik} the permittivity for constant strain, c^E_{ijkl} the stiffness constant for constant electric field, and ρ the mass density.

FEM is one of the most accurate methods for modelling a SAW device as the complete set of partial differential equations is solved by discretizing the model into smaller elements which are connected through nodes. The approximation of the displacement $u_i(x)$ and electric potential $\phi(x)$ of the element by the interpolation function is given by

$$u_i(x) = \sum_n N_n(x)u_{in} \tag{3}$$

$$\phi(x) = \sum_n N_n(x)\phi_n \tag{4}$$

where ϕ_n and u_{in} are the values of the potential and the displacement at the node of the element. $N_n(x)$ is the shape function of the element and the index n denotes the node number of the element.

The modelling of a two-dimensional, 5 × 2-bit Barker sequence encoded, SAW correlator comprising a piezoelectric substrate and two non-uniform input and output IDTs is carried out using ANSYS. Both the input and the output transducers have 20 electrodes each. The input IDT of the structure is modelled as an expander to cause it to generate a coded acoustic wave when a normal pulse or a sinusoidal signal is fed to it. The expander IDT geometry determines the code of the generated acoustic wave. A $5(+++-+) \times 2(++)$-bit Barker sequence is encoded in the output/compressor IDT. This is carried out by coupling the electrodes of the IDT identically to the way they are connected to the positive and negative busbars. The input/expander IDT is an exact replica of the output/compressor IDT when a correlation peak is desired. The response of the device for non-correlating codes can be observed by varying the finger geometry of the input IDT. The structure uses a 64° YX $LiNbO_3$ piezoelectric substrate due to its high electromechanical coupling coefficient, especially for the leaky-SAW (LSAW) propagation mode [9, 10]. The length and the thickness of the substrate are 28λ ($\lambda = 40\ \mu$m) and 5λ, respectively. Aluminium is assumed for the electrodes with a metallization ratio (MR) of 0.5, and an electrode thickness of 3%. The material properties of piezoelectric substrate and electrodes are obtained from [8]. The model consists of approximately 180 000 nodes forming over 60 000 elements. The separation between the IDTs is chosen to be 2λ. This is found to be an optimal distance for improving the gain and keeping the electromagnetic feedthrough, the electromagnetic coupling between the two transducers, under control [11].

3.2. Simulation results

The simulations are aimed at characterizing the full-scale electromechanical phenomenon of the device, subjected to time- and frequency-varying excitation. A frequency sweep is performed using harmonic analysis to determine the response of the correlator for different acoustic modes of interest. Apart from the admittance curve and the electric response calculation, analysis of various acoustic modes is carried out with the help of the displacement, electric field, and stress contours in μMKS units. In this research, the frequency response of the correlator is obtained by driving the input IDT electrodes with an alternating voltage of ±10 V. The harmonic analysis is carried out for a wide frequency range. Depending on the excitation frequency, various acoustic wave modes such as SAWs or bulk acoustic waves (BAWs) are excited. They are analysed by observing the contour plots, e.g. displacement, potential, and stress, of the structure.

The harmonic admittance which characterizes the electrical behaviour of the SAW correlator is determined from the complete charge distribution of the electrodes. If q is the complex charge of the electrode then the admittance Y is defined as [12]

$$Y = j\frac{q\omega}{V}, \tag{5}$$

where ω is the angular frequency.

As can be seen from figure 4(a), the magnitude of the complex admittance attains a high value at the resonant frequencies and hence exhibits a strong peak. The two admittance peaks to the left of the admittance curve, at frequencies of 89.3 and 90.5 MHz, are those corresponding to the symmetric and antisymmetric surface acoustic wave modes. In the middle part of the admittance curve, bulk acoustic wave modes are observed on the basis of the wave propagation into the bulk of the substrate. The mode at 100.4 MHz is a leaky surface acoustic wave (LSAW) where both the surface and bulk wave propagations are observed.

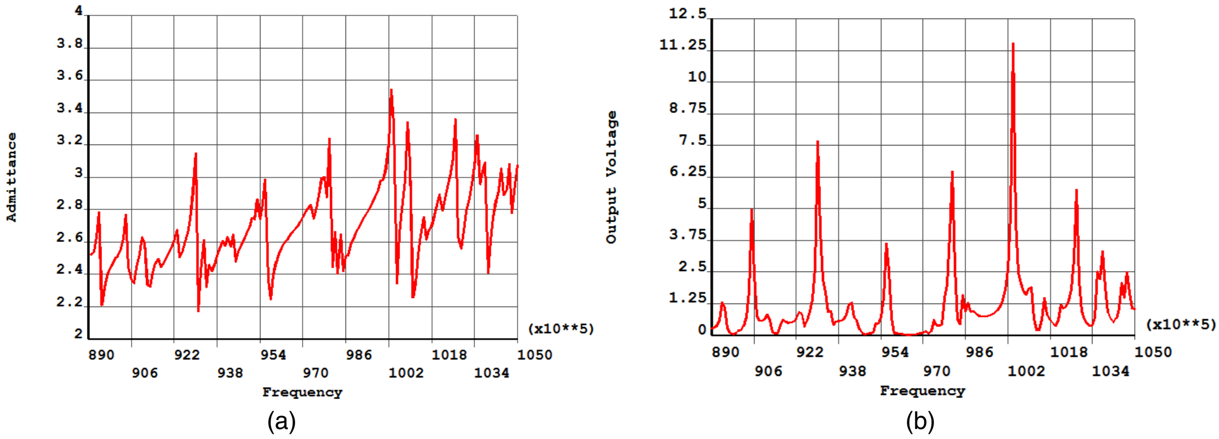

Figure 4. (a) Frequency response of the correlator when the code matches the admittance curve. (b) Magnitude of the voltage across the output IDT.

The output voltage response of the correlator is determined by the electromechanical coupling energy E_c given by [13]

$$E_c = -\tfrac{1}{2} S_{ij}^{T} [e] E_k, \tag{6}$$

where S_{ij}^{T} is the strain vector with constant stress, $[e]$ is the piezoelectric stress matrix, and E_k is the electric field vector.

Figure 4(b) shows the output voltage response of the correlator, when the code matches, for different acoustic modes determined by the excitation frequency. The modes definitely affect the response of the correlator and as can be seen from the figure 4(b). Hence, it is desirable to operate the correlator in the LSAW mode to achieve high electromechanical coupling. The response of the correlators is then electrostatically coupled to the microchannel, as discussed in section 4.

4. Microchannel electrostatic actuation

The fast response times of electrostatic actuators make them an appropriate choice for high-speed ultrasonic applications. However, the usage of electrostatic actuation to achieve moderate displacements is challenging in a wireless environment. This is mainly due to the trade-off between the applied voltage and the gap between the electrodes. If the air gap between the diaphragm and the compressor IDT is increased then the required amplitude of the interrogating signal to actuate the microvalve becomes extremely high. On the other hand, if the air gap is small, the diaphragm might run the risk of shorting with the compressor IDT. Therefore, the usage of two identical SAW correlators with two diaphragms is a way of addressing this problem and hence optimizing the microchannel deflection.

4.1. Geometry

In our current microchannel model, as shown in figure 5, the actuating field is between a 2 μm thick polyimide diaphragm and the output IDT of the correlators, separated by a 1.5 μm air gap. A biocompatible polyimide is chosen as the diaphragm material due to its high conductivity and low Young's modulus.

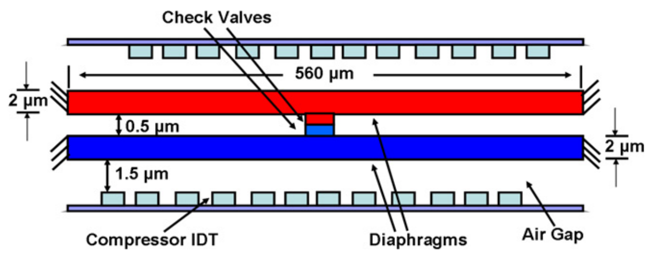

Figure 5. Microchannel electrostatic model.

The length of the edge-clamped diaphragms (560 μm) is determined by the length of the output IDT of the correlators. Short diaphragm lengths consume less die area and increase the resonant frequency of the actuator. Longer diaphragms, however, reduce operating voltage requirements [14]. While design rules limit how close a diaphragm can be to a SAW correlator, manufacturing issues limit the thickness of the diaphragm. The flexible electrode or conducting diaphragm is electrically connected to ground, while the voltage at the fixed electrode or output IDT of the SAW correlator is determined by the input interrogating BPSK signal. The electrostatic force is generated due to the electric field between the interdigitated fingers and the diaphragms. Thus this attractive force results in the centre deflection of the diaphragms towards the compressor IDTs of the correlators. The nodal electrostatic force $\{F^{E}\}$ that causes the microchannel deformation can be expressed as [13]

$$\{F^{E}\} = \int_{\mathrm{vol}} [G]^{T} \{\sigma^{M}\} \mathrm{d(vol)}. \tag{7}$$

In equation (7), $[G]^{T}$ is the strain–displacement matrix based on the element shape functions $N_n(x)$ described in equations (3) and (4), and $\{\sigma^{M}\}$ is the Maxwell stress vector given by

$$\{\sigma^{M}\} = \tfrac{1}{2}(\{E_k\}\{D\}^{T} + \{D\}\{E_k\}^{T} - \{D\}^{T}\{E_k\}[I]), \tag{8}$$

where $\{E_k\}$ and $\{D\}$ are the electric field intensity and electric flux density vectors, respectively, in the electrostatic domain and $[I]$ is the identity matrix.

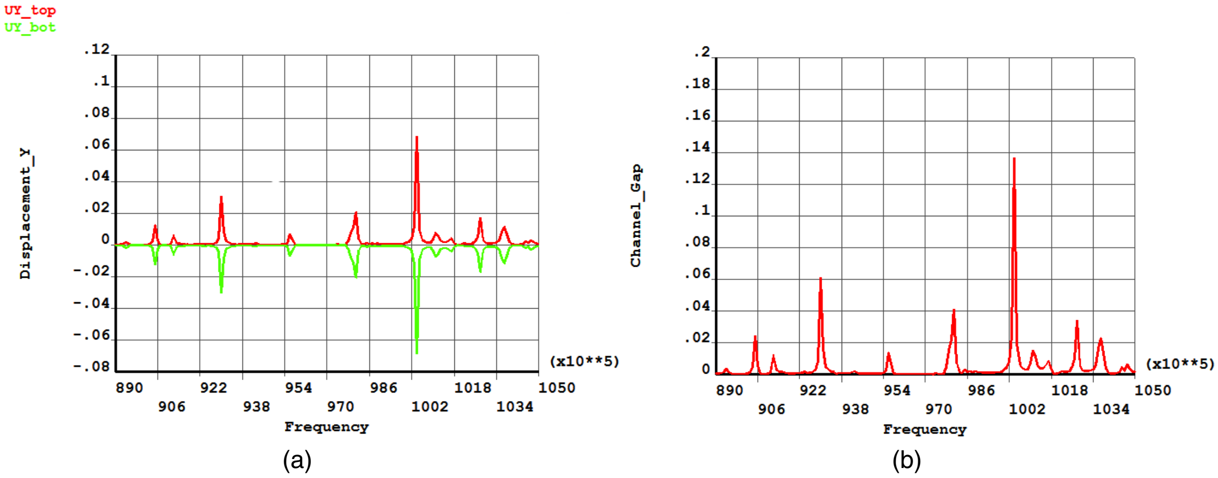

Figure 6. (a) The centre deflection of the diaphragms when the code matches in the y-direction. (b) The channel gap between the check valves.

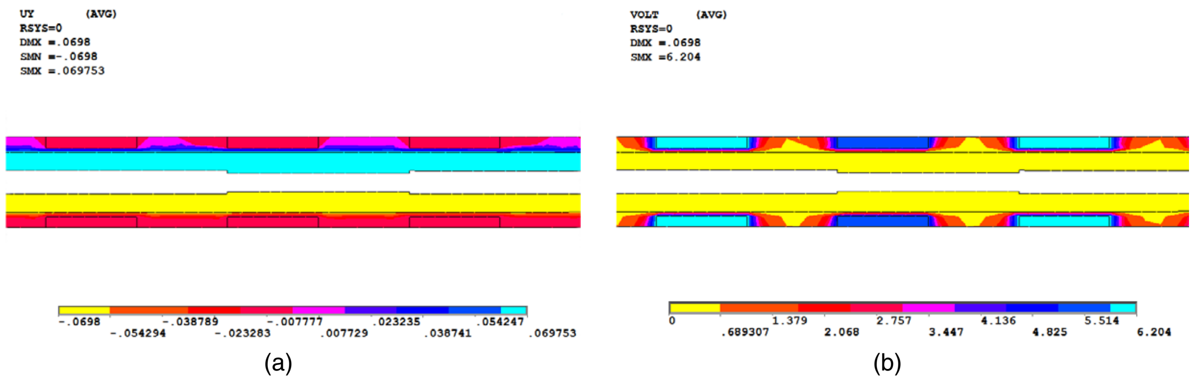

Figure 7. Contour plots of the check valves at LSAW modal frequency: (a) y-displacement contour; (b) electric potential contour.

It suffices to carry out a 2D modelling of the device without compromising the design accuracy. This is because the movable electrode is assumed to move as a parallel plane, rather than as a flexible membrane. This assumption is reasonable for an actuator having a large width-to-gap ratio as the lateral electrode dimensions are assumed to be much larger than the gap spacing. Hence, the volume integral in equation (8) reduces to a surface integral for the current model.

4.2. Simulation results

The main objective in the evaluation of the microvalve is to measure the centre deflection of the microchannel when the correlator is interrogated with a matched and mismatched BPSK signal. Figure 6(a) shows the centre deflection of both diaphragms in the y direction, when the code matches, for different acoustic modes determined by the excitation frequency. Substantial microchannel displacement can be observed in the vicinity of the excited modal frequencies of the correlator. Hence, the electrostatic analyses of the microchannel for a widely varying range of frequencies acts as an effective method for displacement optimization. This allows us to pick the operating mode of interest for displacement optimization. From figure 6(b), a maximum separation of the check valves of 138 nm can be observed at the LSAW mode at 100.4 MHz. The y-displacement contour and the electric potential contour of the check valves at the same modal frequency are given in figure 7 to analyse the microchannel opening. Even though this displacement is small compared to thermal and piezoelectric bimorph actuators, the high-frequency operation of the microvalve results in high particle velocities [15]. The diaphragm deflection can be further increased by employing corrugated diaphragm structures or by considering correlators encoded with a longer code, which in turn increases the diaphragm length. This could not be implemented in the current work due to the huge constraint imposed by such a correlator modelling technique on the available computational resources.

So far the results have been confined to the instance when there is a code match between the input signal, in this model the expander IDT, and the compressor IDT of the correlator. The functionality of the microvalve can only be verified by observing the microchannel deflection to a mismatched input code. This is carried out by varying the electrode coupling of the expander IDT. The response of the microchannel to two different codes, a delay line input and another non-correlating input, at the LSAW mode of interest is provided in figures 8(a)

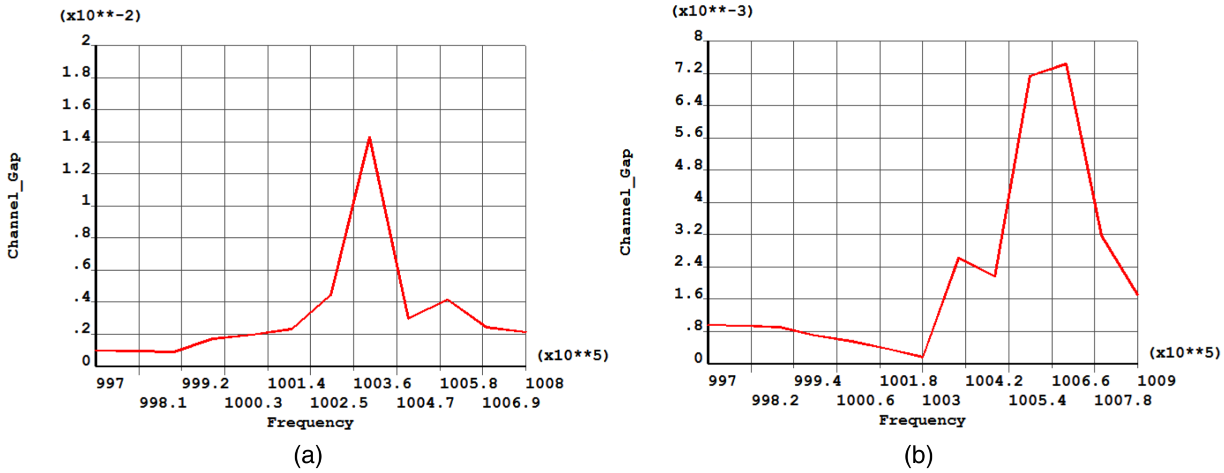

Figure 8. The channel gap between the check valves when the code mismatches (a) for a delay line input (b) for a non-correlating input.

and (b). All the other specifications of the model are kept the same except for the mismatched input code.

By comparing these responses with the correlating microchannel deflection response of figure 6 it can be established that in addition to the excitation frequency, the microvalve's response is determined by the code in the RF signal. Even in the case of a delay line input, when the two codes are very similar, the deflection response of the microvalve is reduced by an order of magnitude from its response to the matched code, as can be seen from figures 8(a).

5. Conclusion

This paper has presented the modelling and simulation of a novel wireless active microvalve by taking into account both the electro-acoustic and electrostatic mechanisms in a single finite element run. The requirements placed by current and emerging biomedical applications on these devices, such as small size and remote interrogability, are taken into consideration. The results discussed in this work include: (i) comprehensive FEM modelling of a two-dimensional, 5 × 2-bit Barker sequence encoded SAW correlator and (ii) detailed study of the microchannel deflection caused by electrostatically coupling the output IDTs of the SAW correlators to the microchannel, actuation optimization by operating the device at the LSAW mode, and analysis of difference in microchannel deflection when there is a code mismatch. It is concluded that the model appropriately represents the interrogating signal code dependent operation and the excited acoustic mode dependent operation of the microvalve and hence enabled analysis of the microchannel deflection. On the basis of such an actuation analysis with the developed FEM model, a microfluidic device with more optimal performance is expected to be designed for various applications.

Acknowledgments

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