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FREQUENCY-CONTROLLED WIRELESS PASSIVE MICROFLUIDIC DEVICES

MARWAN NAFEA MINJAL

A thesis submitted in fulfillment of the
requirements of the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
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DECLARATION

I declare that this thesis entitled "*Frequency-Controlled Wireless Passive Microfluidic Devices*" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ABSTRACT

Microfluidics is a promising technology that is increasingly attracting the attention of researchers due to its high efficiency and low-cost features. Micropumps, micromixers, and microvalves have been widely applied in various biomedical applications due to their compact size and precise dosage controllability. Nevertheless, despite the vast amount of research reported in this research area, the ability to implement these devices in portable and implantable applications is still limited. To date, such devices are constricted to the use of wires, or on-board power supplies, such as batteries. This thesis presents novel techniques that allow wireless control of passive microfluidic devices using an external radiofrequency magnetic field utilizing thermopneumatic principle. Three microfluidic devices are designed and developed to perform within the range of implantable drug-delivery devices. To demonstrate the wireless control of microfluidic devices, a wireless implantable thermopneumatic micropump is presented. Thermopneumatic pumping with a maximum flow rate of 2.86 μL/min is realized using a planar wirelessly-controlled passive inductor-capacitor heater. Then, this principle was extended in order to demonstrate the selective wireless control of multiple passive heaters. A passive wirelessly-controlled thermopneumatic zigzag micromixer is developed as a mean of a multiple drug delivery device. A maximum mixing efficiency of 96.1% is achieved by selectively activating two passive wireless planar inductor-capacitor heaters that have different resonant frequency values. To eliminate the heat associated with aforementioned wireless devices, a wireless piezoelectric normally-closed microvalve for drug delivery applications is developed. A piezoelectric diaphragm is operated wirelessly using the wireless power that is transferred from an external magnetic field. Valving is achieved with a percentage error as low as 3.11% in a 3 days long-term functionality test. The developed devices present a promising implementation of the reported wireless actuation principles in various portable and implantable biomedical applications, such as drug delivery, analytical assays, and cell lysis devices.

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LIST OF ABBREVIATIONS

°C	-	Degrees Celsius
3D	-	Three-dimensional
A	-	Ampere
AC	-	Alternating current
CAD	-	Computer-aided design
C	-	Capacitor
cm	-	Centimeter
cm^2	-	Squared centimeter
cm^3	-	Cubic centimeter
DI	-	Deionized
DNA	-	Deoxyribonucleic acid
Exp.	-	Experimental
F	-	Farad
FEA	-	Finite element analysis
g	-	Gram
H	-	Henry
h	-	Hour
Hz	-	Hertz
IR	-	Infrared
K	-	Kelvin
k	-	Kilo
kg	-	Kilogram
kHz	-	Kilohertz
kPa	-	Kilopascal
kΩ	-	Kiloohm
L	-	Inductor
LC	-	Inductor-capacitor

LOC	-	Lab-on-a-chip
m	-	Meter
mA	-	Milliampere
M	-	Mega
MEMS	-	Microelectromechanical systems
mH	-	Millihenry
MHz	-	Mega hertz
min	-	Minute
mm	-	Millimetre
mm^2	-	Squared millimeter
mm^3	-	Cubic millimeter
mW	-	Milliwatt
n	-	Nano
N	-	Newton
nH	-	Nanohenry
nL	-	Nanoliter
Pa	-	Pascal
PBS	-	Phosphate buffered saline
PC	-	Polycarbonate
PDMS	-	Polydimethylsiloxane
PEA	-	Piezoelectric actuator
pF	-	Picofarad
PI	-	Polyimide
PMMA	-	Poly(methyl methacrylate)
POC	-	Point-of-care
Ref.	-	Reference
RF	-	Radio frequency
rpm	-	Revolutions per minute
s	-	Second
Sim.	-	Simualtion
SMA	-	Shape memory alloy
V	-	Volt
W	-	Watt
WPT	-	Wireless power transfer

μL	-	Microliter
μm	-	Micrometre
μN	-	Micronewton
μTAS	-	Micro total analysis systems

LIST OF SYMBOLS

μ_f	-	Fluid viscosity
A_2	-	Cross-sectional area of the device coil
A_C	-	Cross-sectional area of the microchannel
A_{Co}	-	cross-sectional area of the coil
A_{PDMS}	-	Cross sectional surface area between the LC wireless heater and the heating chamber
A_{Pl}	-	Area of the parallel plates of the capacitor
A_v	-	Polynomial of unknown vibration parameters
A_W	-	Area of the top wall of the chamber
b'	-	Damper coefficient of the piezoelectric actuator and coupled PDMS layers
B_v	-	Polynomial of output lag vibration parameters
c	-	Molar concentration
$\overline{c}$	-	Mean molar concentration of a fully mixed solution
c_{ni}	-	Molar concentration at a point *ni*
C_P	-	Capacitance of the piezoelectric actuator
C_{par}	-	Parasitic capacitance
C_T	-	Tuning capacitor on the transmitter side
C_{th}	-	Effective heat capacity of the air chamber
C_{total}	-	Total capacitance of the planar heater
D	-	*D*iffusion coefficient
d	-	Piezoelectric material constant
$D_{2,j}$	-	Distance between the centers of the *j*-th wire segments
d_{avg}	-	Average diameter of the planar coil
d_C	-	Separation gap between the plates of the capacitor
D_h	-	Hydraulic diameter of the microchannel
d_{in}	-	Inner diameter of the planar coil

d_{out}	-	Outer diameter of the planar coil
E	-	Young's modulus of the membrane of the reservoir
$\dot{E}$	-	Thermal power supplied to the air chamber
f_m	-	Magnetic field frequency
f_o	-	Operating frequency
F_{P-}	-	Force generated by the piezoelectric actuator and the coupled parts during negative parts of the voltage signal
F_{P+}	-	Force generated by the piezoelectric actuator and the coupled parts during positive parts of the voltage signal
F_{P0}	-	Force exerted by the piezoelectric actuator and the coupled parts when no voltage is applied
F_R	-	Force exerted by the reservoir
f_r	-	Resonant frequency
f_{rP}	-	Resonant frequency of the unloaded piezoelectric actuator
f'_{rP}	-	Resonant frequency of the loaded piezoelectric actuator
g^{-1}	-	Time-shift operator
h_{air}	-	Effective heat transfer coefficient of the walls of the air chamber to the surroundings
h_{max}	-	Maximum height of the membrane of the reservoir
i	-	Number of the segments of the coil
i_1	-	Total current of the device coil
i_2	-	Total current of the external coil
j	-	Number of segments pairs of the coil
k	-	Thermal conductivity
k'	-	Stiffness of the piezoelectric actuator and coupled PDMS layers
K_1	-	Layout dependent constant 1
K_2	-	Layout dependent constant 2
k_B	-	Boltzmann constant
L	-	Inductor
l	-	Length of the coil
L_1	-	Inductance of the external coil
L_2	-	Inductance of the device coil

l_2	-	Total length of the device coil
$l_{2,i}$	-	Length of the *i*-th wire segment of the device coil
$L_{2,i}$	-	Self-inductance value of each wire segment of the device coil
l_C	-	Length of the microchannel
L_{Co}	-	Inductance of the coil
L_{S1}	-	Self-inductance of the device coil
L_{S2}	-	Self-inductance of the external coil
L_T	-	Total inductance measured when the two coils are connected in series
m	-	Effective mass of the unloaded piezoelectric actuator
M	-	Mutual inductance between two coils
m'	-	Effective mass of the piezoelectric actuator and coupled PDMS layers
$M_{2,j}$	-	Mutual inductance of between each pair of wire segments of the device coil
N	-	Number of air molecules enclosed in the air chamber.
n	-	Number of turns
ni	-	point inside the microchannel
n_p	-	Total number of sample points inside the cross-section of the microchannel
P	-	Power consumed in the heater
p	-	Pressure
Pe	-	Peclet number
Q	-	conduction of energy transfer
q	-	Flow rate
r	-	Radius of the microchannel
R	-	Resistance of the coil
r_1	-	Bare radius of the wire of the external coil
R_1	-	Resistance of the external coil
r_2	-	Bare radius of the wire of the device coil
R_2	-	Resistance of the device coil
r_C	-	Diagonal length of the microchannel.
R_C	-	Radial location in the microchannel
Re	-	Reynolds number

R_P	-	Resistance of the piezoelectric actuator
R_s	-	Internal resistance of the voltage source
R_T	-	Thermal resistance to the surroundings
s	-	Deformation of the walls
s_C	-	Separation gap of the planar coil
s_T	-	Total displacement of the piezoelectric actuator
T	-	Absolute temperature
t	-	Time
T_0	-	Room temperature
T_1	-	New temperature
T_{SS}	-	Steady state temperature generated in the heater
u	-	Flow velocity
u_z	-	z-component of the flow velocity
v	-	Electromotive force
V	-	Volume of the gas
V_0	-	Volume of the air in the chamber at room temperature
V_1	-	Volume of the air in the chamber at new temperature
V_D	-	Dispensed liquid volume
v_P	-	Voltage across the piezoelectric actuator
V_{PBS}	-	Volumes of the PBS solution
V_R	-	Volume of the reservoir
v_S	-	Voltage source
$\mathrm{V_T}$	-	Total volume of the PBS and pH 4 buffer solutions
w_C	-	Width of the planar coil
Z_1	-	Total impedance of the device coil
Z_2	-	Total impedance of the external coil
α	-	Parameter that control the shape and the amplitude of the hysteresis loop
α_R	-	Temperature coefficient of the resistance of the circuit
β	-	Parameter that control the shape and the amplitude of the hysteresis loop
γ	-	Parameter that control the shape and the amplitude of the hysteresis loop

δ	-	Skin depth of the conductor
Δh	-	Change in the height of the membrane of the reservoir
Δp	-	Change in pressure inside the air chamber
ΔT	-	Temperature difference between the heater and the chamber
ΔV	-	Volume difference of the air in the chamber
Δx	-	Thickness of the membrane of the reservoir
Δxy	-	Gap separation distance
ε_0	-	Vacuum permittivity
ε_r	-	Dielectric constant of the dielectric material
μ	-	Absolute magnetic permeability
μ_0	-	Magnetivity of free space
ρ	-	Resistivity of the material
ρ_f	-	Fluid density
ρ_{fr}	-	Fill ratio
σ	-	Standard deviation of the molar concentration across the channel
σ_M	-	Standard deviation of the distance travelled by a molecule
σ_{max}	-	Maximum standard deviation at the inlet of the main microchannel
ω	-	Angular frequency of the AC current
Ω	-	Ohm

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Microelectromechanical systems (MEMS) is a promising technology that has enabled various sensors [1], actuators [2], electronics [3], and structures [4] to be realized. This consequently enabled manufacturing a wide range of miniaturized devices using microfabrication techniques [5]. Since the beginning of MEMS development, fluidic devices have captured the attention of researchers, which made them among the first devices to be fabricated in microscale [6]. The rapid development of MEMS-compatible technologies has provided means to continuously develop and miniaturize microfluidic devices, which allowed them to precisely manipulate small volumes of liquids within a short time. In addition, such devices require less human intervention and a lower cost, while maintaining a higher sensitivity and stability when compared to traditional fluidic platforms [7]. Since then, several types of microfluidic devices have been developed, such as micropumps [8], micromixers [9], microvalves [10], microneedles [11], microreservoirs [12], and microchannels [13]. However, the first three types form the majority of the reported microfluidic devices, due to their crucial functions in modern-day microfluidic applications [14-16].

In numerous microfluidic systems, a self-contained micropump is an essential component for precise samples/reagents transport, metering, and delivery [14]. Therefore, micropumping components are often integrated into such systems to achieve a reasonable flow rate and overcome the induced back pressure [16]. In addition to the micropump, the micromixer is another component that plays a core role

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In the last few decades, microfluidic devices for various applications have been developed by researchers from diverse research areas to address the continuous need for precise fluids manipulation on the microscale. These areas are continuously growing and found their way to several biomedical applications that require special consideration to overcome the challenges associated with these applications. To grasp a better understanding on the recent advances in these areas, this chapter presents a literature review on the concept of microfluidics and governing laws of laminar flow. In addition, classifications, working principles, and actuation mechanisms of micropumps, micromixers, and microvalves are covered. Thermopneumatic micropumps, passive zigzag micromixers, and normally-closed piezo-actuated microvalves are further covered, since they are the main subject of this research. Then, an overview of various microactuators for microfluidic devices, including thermopneumatic and piezoelectric microactuators is presented. Furthermore, the review presents the main powering methods for portable and implantable microfluidic devices, as well as their advantages and limitations.

2.2 Microfluidics

Microfluidics is a MEMS discipline that deals with manipulating small volumes of fluids (10^{-18} – 10^{-9} liters) using channels with dimensions of tens to

CHAPTER 3

WIRELESSLY CONTROLLED THERMOPNEUMATIC PASSIVE MICROPUMP

3.1 Introduction

This chapter describes the development of a thermopneumatic micropump with a novel design that does not affect the temperature of the working fluid. The device operates wirelessly through the energy transfer to a frequency-dependent heater, which is placed underneath the heating chamber of the pump. Heat is generated at the wireless heater when the external magnetic field is tuned to the resonant frequency of the heater. The enclosed air in the chamber expands due to heat and forces the liquid to flow out from the reservoir. The device is designed with no moving element, i.e., oscillation of passive check valve and membrane, and thus, ensuring a more durable pumping operation. The wireless flow rate control using the fabricated micropump is carried out as the experimental demonstration of the developed radio frequency (RF) thermopneumatic actuation principle. The developed device is able to pump the liquid in single and multiple strokes, and the flow rate performance is varied by manipulating the value of the heating power. In addition, the micropump is able to pump the liquid when immersed in distilled water for verification of the wireless release in water medium. Furthermore, finite element analysis is performed to study the influence of the heat transfer to the sample liquid. The presented micropump exclusively offers a promising solution in biomedical implantation devices due to its remotely powered functionality, free from bubble trapping and biocompatible feature.

CHAPTER 4

WIRELESSLY-CONTROLLED PASSIVE ZIGZAG MICROMIXER

4.1 Introduction

This chapter presents a novel passive wirelessly controlled thermopneumatic micromixer to address the aforementioned micromixing challenges and to demonstrate the selective wireless control of multiple actuators. Mixing is achieved in a simple zigzag-shaped mixing microchannel due to the use of an efficient pulsatile flow. Mixing is achieved in a relatively short mixing length, and investigated over a low range *Re* values, since the developed micromixer is dedicated to typical microfluidic biomedical applications in which high flow velocities can cause rupture of cells. In addition, the operating temperature required to increase the *Re* value is limited to avoid any potential damage that might occur to the device. Dynamic heat transfer, thermopneumatic actuation and mixing performance are analytically presented and experimentally verified as a demonstration of the proposed mixing technique. The activation switching time is varied to achieve the maximum mixing efficiency. The results suggest that the developed micromixer is a biocompatible potential that is able to provide mixing-ratio controllability. In addition, the geometry of the proposed device is planar and can be fabricated using out-of-clean-room fabrication processes, making it promising for cost-efficient biomedical applications, such as local drug delivery and cell culturing.

CHAPTER 5

WIRELESSLY-CONTROLLED NORMALLY-CLOSED PIEZO-ACTUATED MICROVALVE

5.1 Introduction

This chapter presents a novel wirelessly controlled piezoelectric microvalve to address the aforementioned microvalving issues and to eliminate the heat associated with the wireless devices that are developed in Chapter 3 and Chapter 4. Valving is achieved using a normally-closed microvalve that efficiently controls the flow of the working fluid, which is stored in a pressurized balloon reservoir. The fluid is pumped due to the pressure inside the reservoir, which is opposed by the pressure generated by the microvalve. The resonant frequency used in WPT process was selected carefully to match the operating frequency of the device while considering the resonant frequency of the PEA. WPT, piezoelectric actuation, reservoir pressure, fluid flow, and valving performances were analytically presented and experimentally verified as a demonstration of the proposed valving technique. Valving performance is initially characterized in air then in phosphate buffered saline (PBS) solution to mimic the drug release kinetics into humans' interstitial body fluids [55, 238]. The activation switching time of the microvalve is varied to achieve different desired flow rates over different periods of time. The performance of the device is investigated over low flow rates that are within the typical range of implantable drug delivery devices. Programmed short-term delivery and 3 days long-term functionality tests are carried out to investigate the valving performance of the device. The results suggest that the developed microvalve is a biocompatible potential, and the proposed concept can be possibly used in biomedical applications, such as drug delivery devices. In addition,

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

In this thesis, wirelessly-controlled microfluidic devices and their applications have been reported. The overall description of the research, which includes the design, modeling, simulation, fabrication, experimental verification, and characterization of the developed wireless microfluidic devices is presented. This chapter presents a summary of the contributions from the work conducted, and the future direction of this research.

6.1 Conclusions

This research presented the great potential of the wireless control of three types of microfluidic devices, namely, a thermopneumatic micropump, a passive zigzag thermopneumatic micromixer, and a normally-closed piezoelectric microvalve. Previous research reported that these devices have a wide range of biomedical applications, since they offer a smaller size, lower cost, higher sensitivity and stability, and require less human intervention when compared to traditional fluidic platforms. The current micropumps, micromixers, and microvalves show limitations in their fabrication methods and performance, as well as the ability to implement them in portable and implantable applications. These issues have been improved by developing new designs, utilizing out-of-clean-room fabrication methods, and developing passive devices that can be wirelessly powered and controlled. The research contributions are presented in the following sequence.

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