Design, Characterisation and Optimisation of a SAW Correlator Driven, Wireless, Passive Microvalve For Biomedical Applications

by

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Contents

Abstract

The culmination of rapid advances made in the areas of microelectromechanical systems (MEMS), nonregenerative power sources, nanotechnology, and biomedical engineering have resulted in the expansion of their horizons in modern medicine for the deployment of a wide array of implantable devices. However, the lifetime and remote interrogability of implants, specifically used for drug delivery applications, has been an issue of contention, as their deployment period is limited by the battery life and the device size. Furthermore, not much research effort is directed towards remotely controlled flow manipulation using passive components. These shortcomings are addressed in this thesis by employing surface acoustic wave (SAW) technology to design a novel RF powered, secure coded, active microvalve with fully passive components. By combining the complex signal processing capabilities of the acoustic wave correlator with the electrostatic actuation of the microchannel, the advantages of both the mechanisms are incorporated into a novel microvalve design. Fluid pumping can be achieved at ultrasonic frequencies by electrostatically actuating the edge clamped microchannel, placed in between the compressor interdigital transducer's (IDT's) of two identical SAW correlators. The ability to wirelessly administer doses of drug accurately, for an extended period of time, at an inaccessible target location, through an implanted microvalve has the potential to revolutionise health care for long-term, controlled drug release applications.

Three specific and diverse areas within MEMS, the new device builds on, are investigated by taking a comprehensive design, modelling, optimisation and experimental validation approach for majority of the research endeavors in the thesis. The first area corresponds to SAW technology followed by microfluidics, and body-centric communications; driven by the ultimate goal to demonstrate the operational feasibility of a human implanted, wirelessly controlled microvalve. The proposed specialised design necessitated a thorough understanding of the multiple coupled physics phenomena at the process level, before fabrication, for the critical investigation and refinement of the individual microvalve components. A comprehensive finite element modelling technique, where the complete set of partial differential equations are solved, was used to design these microvalve components with low level of abstraction to enable an automatic inclusion of the majority of the second order effects.

As a starting point for the FEM modelling of SAW devices, an infinite periodic grating was modelled to analyse the freely propagating eigenmodes and eigenvalues with modal analysis; and electrically active waves and electrical admittance with harmonic analysis. A curve fitting technique was employed to extract the COM/P-matrix model parameters from these FEM results. Furthermore, an experimental validation of the parameters extracted using this novel combination of FEM and fitting techniques was carried out by fabricating a number of delaylines and comparing the physical structure response with the formulated P-matrix model. On the other hand, the modelling of a 2 and 3-dimensional, 5×2-bit Barker sequence encoded acoustic wave correlator was demonstrated using FEM. The correlator's response was quantified in terms of harmonic analysis, to obtain the electrical admittance and output voltage profile, and transient analysis, to study the acoustic wave propagating characteristics and correlation pulses. The validation of these simulation results was carried out by fabricating the SAW correlators using optical lithographic techniques. A good agreement between the numerical and experimental results highlighted the feasibility and potential of using FEM for application specific modelling of SAW correlators.

The complexity involved in combining the electroacoustic correlation and electrostatic actuation mechanisms, necessitated a systematic design and optimization of the novel microvalve which is best possible with FEM. In this thesis, the emphasis was on the design and optimisation of a novel microfluidic structure through the deflection analysis, both, to verify the functionality of the concept and to investigate the working range of the structure. Secure interrogability of the microvalve was demonstrated by utilising finite element modelling of the complete structure and the quantitative deduction of the code dependent, harmonic and dynamic transient microchannel actuation. A numerical and experimental analysis of the biotelemetry link for the microvalve was undertaken in the vicinity of numerical and physical human body phantoms, respectively. To accurately account for the path losses and to address the design optimisation, the receiver coil/antenna was solved simultaneously with the transmitter coil/antenna in the presence of a human body simulant using 3-dimensional, high frequency electromagnetic, FEM modelling. The received relative signal strength was numerically and experimentally derived for a miniature (6×6×0.5 mm), square spiral antenna/coil when interrogated by a hand-held 8×5×0.2 cm square spiral antenna/coil in the near field. Finally, the experimental results confirmed well with the FEM analysis predictions and hence ascertained the applicability of the developed system for secure interrogation and remote powering of the newly proposed microvalve.

Statement of Originality

Name: Ajay Chandra Tikka　　　　Program: Doctor of Philosophy (PhD)

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Abbreviations and Symbols

Abbreviations

AC	**A**lternating **C**urrent
BAW	**B**ulk **A**coustic **W**ave
BEM	**B**oundary **E**lement **M**ethod
BPSK	**B**inary **P**hase **S**hift **K**eying
COM	**C**oupling **O**f **M**odes
DC	**D**irect **C**urrent
DIL	**D**ual **I**n **L**ine
DOF	**D**egress **O**f **F**reedom
EM	**E**lectro**m**agnetic
FDS	**F**requency **D**omain **S**ampling
FDTD	**F**inite **D**ifference **T**ime **D**omain
FEM	**F**inite **E**lement **M**ethod
FM	**F**requency **M**odulation
HFEM	**H**ybrid **F**inite **E**lement **M**ethod
IDT	**I**nter**d**igital **T**ransducer
LSAW	**L**eaky **S**urface **A**coustic **W**ave
MEMS	**M**icro**e**lectro**m**echanical **S**ystems
MLS	**M**aximum **L**ength **S**equence
MR	**M**etallization **R**atio
PBC	**P**eriodic **B**oundary **C**ondition
Q-factor	**Q**uality **F**actor
RF	**R**adio **F**requency
RFID	**R**adio **F**requency **Id**entification
RTO	**R**emote **T**urn **O**n
SAW	**S**urface **A**coustic **W**ave
SDA	**S**pectral **D**omain **A**nalysis
SEM	**S**canning **E**lectron **M**icroscope
STW	**S**urface **T**ransverse **W**ave
TDS	**T**ime **D**omain **S**ampling
UV	**U**ltra **V**iolet

Symbol	Name	Unit
$\mathbf{a}$	displacement vector	m
A	delayline admittance matrix	mixed
A_0	overlapping area	m^2
B	bandwidth	Hz
$B(f)$	susceptance	S
c	loaded wavenumber	rad/m
c	stiffness	N/m^2
C	capacitance	F
C_n	normalised capacitance	F
C_p	periodic capacitance	F
D	electrical flux	C/m^2
DR_o	dispersion relation for open circuit grating	-
DR_s	dispersion relation for short circuit grating	-
d	distance	m
E	electric field	V/m
E_c	electromechanical coupling energy	J
E_k	electric field vector	V/m
e	piezoelectric stress constant	C/m^2
F	force	N
F_E	electrostatic force	N
F^E	nodal electrostatic force	N
F_N	noise figure	dB
$\mathbf{F}^N$	nodal force vector	N
$\mathbf{F}^{TH}$	thermal force vector	N
f_c	center frequency	Hz
f_B	bit rate	Hz
f_{M+}	anti-symmetric SAW modal frequency	Hz
f_{M-}	symmetric SAW modal frequency	Hz
G	gain	-
$G(x)$	Green's function	mixed
$G(f)$	conductance	S
$G(f)$	transfer function	mixed
$[G]$	strain-displacement matrix	mixed
g	spacing between coil turns	m
H	magnetic field strength	A/m

Symbol	Name	Unit
I	current	A
$[I]$	identity matrix	-
j	unit imaginary number	-
K	Boltzmann's constant	-
$[K]$	structural stiffness matrix	mixed
$[K_d]$	dielectric permittivity matrix	mixed
L	IDT length	m
L	inductance	H
L_{eff}	effective inductance	H
l_{avg}	average diameter of the square spiral	m
l_{tot}	total length of the square spiral	m
M	mutual inductance	H
$[M]$	mass matrix	mixed
$[N]$	structural shape function	mixed
$[N_E]$	electrical shape function	mixed
N_B	binary bits	-
n	normalised wavenumber	-
n	number of coil turns	-
P	power	W
$P(f)$	P-matrix	mixed
p	period of the grating	m
p_a	radiation pressure	Pa
Q	quality factor	-
q	complex charge of the electrodes	C
q_n	nodal charge density	C/m
R	resistance	Ω
$\mathbf{R_s}$	residual vector of elastostatic field	-
$\mathbf{R_e}$	residual vector of electromechanic field	-
S	strain	-
S_{12}	insertion loss	dB
S_P	power density	W/m^2
SNR	signal-to-noise ratio	-
T	stress	N/m^2
T_C	temperature	°C
T_B	bit time	sec

Symbol	Name	Unit
t_s	substrate thickness	m
u	particle displacement	m
V	voltage	V
v_i	nodal electrical potential	V
W	width of the coil	m
Y	admittance	S
Z	impedance	Ω
ω	angular frequency	rads^{-1}
μ	propagation constant	-
μ_0	permeability of vacuum	Vs/Am
λ	wave length	m
λ_t	wave length in lossy medium	m
ν	Velocity	m/s
δ	normalised COM wavenumber	-
κ	COM reflection	-
γ	COM attenuation parameter	Nep/m
α	COM transduction parameter	$\Omega^{-1/2}$m^{-1}
ϵ	permittivity	F/m
ϵ_r	relative dielectric constant	-
ϵ_t	complex permittivity	F/m
ρ	mass density	kg/m^3
ϕ	electrical scalar potential	V
σ	conductivity	S/m^2
∇	gradient of a scalar field	m^{-1}
$\nabla.$	divergence of a vector field	m^{-1}
Θ_D	diffraction angle	-
σ^M	Maxwell stress vector	N/m^2
δ_p	penetration depth	m
æ	fill ratio	-
δ_c	skin depth	m

Publications

Book Chapter Publications

1. TIKKA-A., AL-SARAWI-S., AND ABBOTT-D. (2009). Loading analysis of a remotely interrogatable passive microvalve, *Recent Advances in Sensing Technology - Lecture notes in Electrical Engineering Series*, Springer-Verlag, Accepted for Publication.

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