Implantable Microelectronics for Biological Signals

A dissertation presented
by
Anthony Nikola Laskovski
to
The School of Electrical Engineering and Computer Science
for the degree of
Doctor of Philosophy
in the subject of
Electrical Engineering
The University of Newcastle
Australia
October 2011
Statement of Originality

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying subject to the provisions of the Copyright Act 1968.

Date Author’s signature
Ageing populations in the developed world are perhaps one of the greatest concerns for providing quality healthcare in the future. Medical professionals are dependent on non-biological technology in order to understand how the human body works. Electronics has been a relatively recent area of science, and it has seen an escalating rate of sophistication. The body’s nervous system operates by using electrical signals, and from an engineering perspective the body’s organs behave as sensors and transducers. The ability to monitor vital health indicators such as the electrocardiogram (ECG), body temperature and blood pressure information via medical telemetry may offer adequate tools to view the logged or real time data of vulnerable patients, especially the elderly. Miniaturising this technology will also open new opportunities to access more biological information. Growing telecommunications infrastructure with increasing sophistication is opening the possibilities with regards to medical telemetry, making it theoretically possible for patients to carry out their daily tasks while being remotely monitored by doctors.

Implantable electronics have become a topic of considerable research, with the implementation of the Cochlear implant and more recently Retinal prosthesis, in addition to telemetry devices. Implantable telemetry is also used in biomedical research
Abstract

to identify the physiological activity of animal subjects in confined laboratory environments. This dissertation presents new techniques in data and power transfer applied to implantable devices in the body. In particular it studies high frequency inductive links to reduce the size of implantable devices. It introduces the concept of Class-E oscillators, which combines Class-E amplifiers commonly used in inductive power transfer links, with oscillators, increasing the overall efficiency of the wireless power transmitter. A multi-array technique is implemented in power-transmitting coils to provide continuous wireless power to implants despite movements by laboratory animals in an enclosed environment. At the implant site, this thesis presents stacking techniques for power-receiving coils in order to increase the efficiency and reduce the physical size of the implanted power coil. An antenna has been implemented to transmit data from the implant to a site external to the body while the implant is loaded in tissue. A unique type of implant architecture is also proposed which generates harmonic signals, one harmonic of which forms the data carrier frequency thus avoiding the need for an oscillator block in the implant.

The supply of power to implants may not always be conducted with a battery, and much effort has been committed to investigate ways of transmitting power wirelessly, mainly with inductive links. Switching power amplifiers, in particular Class-E amplifiers, are known for operating efficiently at high frequencies. This thesis will offer a simple way to analyse and design Class-E amplifiers using second order principles in the Laplace domain. Further investigation of Class-E amplifiers also leads to the concept of Class-E self oscillation for wireless power delivery to implants. Power amplifiers and oscillators are considered as two separate blocks in wireless power
transmission. By combining these topologies into a self-oscillating power transmitter, greater efficiency has been achieved. Various topologies of Class-E oscillators as inductive power transmitters are compared with measured hardware results, determining that a crystal feedback network provides both accuracy and high output power. The thesis includes modeling, a design process and the hardware implementation of an ISM-band 27MHz Class-E oscillator as a power transmitter to an implant through biological tissue. A power of 27.5dBm was transmitted through 2cm of beef and 20.6dBm was received on the power-receiving implanted coil.

The transmission of power occurs more efficiently at lower frequencies, however this requires transmitting and receiving coils with larger dimensions. Space restrictions in the implantable environment naturally leads to a need to transmit power at higher frequencies. This dissertation presents an inductive power transmission coil for biosensor-based telemetric implants. Using stacked spirals reduces the consumed space and also the self-resonant frequency (SRF) of the spiral, in addition to the required power transmission frequency for the implanted device. A four-layer 15mm x 15mm spiral coil of seven turns is simulated in CST Microwave Studio (TM), constructed and tested in hardware with comparable results. Measurements also include the receipt of power inductively from an energised array of spirals powered by a Class-E transmitter at 27MHz, and rectified to 1V, which is sufficient to drive an implant.

This dissertation also investigates the design procedures of the Class-E amplifier as a data-transmitter for biotelemetry systems using different modulation techniques. A Class-E data-transmitter circuit that produces On-Off Keying (OOK), Frequency Shift Keying (FSK) and Phase Shift Keying (PSK) modulated signals has been de-
signed, optimised and analysed in terms of a second order system for general implantable electronics. This development will provide flexibility and offer increased performance for implantable devices.

It is generally preferred that the power and data signals for telemetric implants are supplied by two different frequency levels due to different tissue absorption levels at various frequencies. An implant’s data carrier frequency is traditionally generated by an oscillator block within the implant. At higher frequencies such as the Medical Implant Communication Service band (MICS: 401-406MHz) this can potentially require a significant amount of power. This thesis presents a harmonics based telemetry system for implantable devices. The outlined system generates harmonics from the power signal within the implant to create a carrier frequency for data transmission at the fifteenth harmonic within the MICS band, 405MHz. The prototype is capable of operating in a multi-user system using available frequency bands for medical use.
# Contents

Title Page ................................................................. i
Abstract ................................................................. iii
Table of Contents ......................................................... vii
List of Figures ........................................................... x
List of Tables ............................................................ xv
Citations to Author’s Publications .................................... xvi
Acknowledgments ........................................................ xvi
Dedication ................................................................. xx

1 Introduction ........................................................... 1
  1.1 Technology in Medicine ............................................ 2
  1.2 Electronics in Medicine ........................................... 3
  1.3 Implantable Electronics .......................................... 5
  1.4 Thesis Outline ..................................................... 9
  References .............................................................. 12

2 Background .......................................................... 14
  2.1 Power Supply ....................................................... 15
  2.2 Power Transmitter Circuits ....................................... 17
    2.2.1 Class-F Amplifiers ........................................... 18
    2.2.2 Class-D Amplifiers .......................................... 19
    2.2.3 Class-E Amplifiers ........................................... 21
  2.3 Wireless Power Links ............................................. 24
  2.4 Rectification ...................................................... 28
  2.5 Data Carrier Generation ......................................... 31
  2.6 Modulation Techniques ......................................... 32
  2.7 Summary .......................................................... 35
  References .............................................................. 37
3 Analysis of Power Transmitters for High-Frequency Wireless Power Links

3.1 Background .......................................................... 47
3.2 Class-E Amplifier in the s-Domain ................................. 48
3.3 Self Resonant Inductors and $C_3$ in Class-E Transmitters ....... 53
3.4 Conclusion ............................................................ 60
References ................................................................. 61

4 Class-E Oscillators for Wireless Power Transmission

4.1 Introduction ............................................................ 64
4.2 Comparison of Class-E Oscillator Topologies ....................... 72
  4.2.1 Class-E Oscillators Biased with Resistors .................... 74
  4.2.2 Class-E Oscillators biased with Diodes ....................... 76
4.3 Modelling the Class-E Oscillator .................................. 79
4.4 Wireless Power Transfer ............................................ 82
4.5 Conclusion ............................................................ 84
References ................................................................. 87

5 Coil Design Techniques for Wireless Power Links

5.1 Introduction ............................................................ 90
5.2 Spiral Coils ............................................................ 92
5.3 Transmission Coils ................................................... 94
5.4 Stacked Spirals in Power Receivers ................................. 95
  5.4.1 Parametric Analysis ........................................... 99
  5.4.2 Hardware Measurements ....................................... 104
  5.4.3 Discussion ................................................... 111
5.5 Conclusion ............................................................ 112
References ................................................................. 114

6 Class-E Amplifiers as Data Transmitters

6.1 A Class-E transmitter with mixed modulation signals ............ 119
6.2 Circuit Simulations .................................................. 120
6.3 Conclusion ............................................................ 128
References ................................................................. 129

7 A Low Power Harmonics Based Telemetry System

7.1 Harmonics in Common Electrical Signals ......................... 131
7.2 Harmonic-Based Telemetry Architecture .......................... 136
7.3 A Prototype System for a MICS Data Link ......................... 139
7.4 Multi-Device System ................................................ 152
7.5 Comparisons ......................................................... 153
7.6 Conclusion ............................................................ 155
List of Figures

1.1 United Nations median age projections until 2050 [1]. .............. 2
1.2 Anatomy of the human ear [13]. ........................................... 7
1.3 Anatomy of the human eye [13]. ............................................. 7
1.4 General architecture of a prosthetic electronic implant. .............. 8
1.5 General architecture of a telemetric electronic implant. .............. 8

2.1 A block diagram showing the structure of the project and literature review. ................................................................. 15
2.2 The class-F power amplifier. .................................................... 19
2.3 Class-D power amplifier. .......................................................... 20
2.4 Class-E power amplifier. .......................................................... 22
2.5 Voltage across $C_1$ for one period. ........................................ 22
2.6 Illustration of an inductive wireless link for implantable devices. .... 24
2.7 A diagram of a wire-wound helix coil of length $l$ and radius $r$ ....... 26
2.8 A diagram of an Archimedean spiral. ....................................... 27
2.9 A diagram of a square spiral. ................................................... 28
2.10 Diode Rectifier ................................................................. 29
2.11 Bridge Rectifier ................................................................. 29
2.12 Class-E Rectifier ............................................................... 30
2.13 Active Diode [40]. ............................................................. 31
2.14 Frequency Shift Keying (FSK). .............................................. 32
2.15 On-Off Keying (OOK). .......................................................... 33
2.16 Binary Phase Shift Keying (BPSK). ......................................... 34

3.1 The Class-E amplifier .............................................................. 47
3.2 A clock signal split up into several time-displaced step inputs .......... 49
3.3 Small signal model of the Class-E amplifier ............................... 49
3.4 Class-E power transmitter with parasitic capacitor $C_3$ .................. 54
3.5 Small signal model of a Class-E power transmitter with parasitic capacitor $C_3$ ................................................................. 54
3.6 Voltage across 10 Ω resistor in a 20MHz Class-E power transmitter with traditional specifications. .......................... 56
3.7 Voltage across 10 Ω resistor in a 133MHz Class-E power transmitter with traditional specifications. .......................... 57
3.8 Voltage across 10 Ω resistor in a 403MHz Class-E power transmitter with traditional specifications. .......................... 57
3.9 Voltage across 10 Ω resistor in a 20MHz Class-E power transmitter with self resonant inductor. .......................... 58
3.10 Voltage across 10 Ω resistor in a 133MHz Class-E power transmitter with self resonant inductor. .......................... 59
3.11 Voltage across 10 Ω resistor in a 403MHz Class-E power transmitter with self resonant inductor. .......................... 59

4.1 The Class-E amplifier. .......................................................... 65
4.2 Timing diagram of $v_{in}$ of a Class-E Amplifier 27MHz. .......... 67
4.3 Timing diagram of $v_{C1}$ of a Class-E Amplifier 27MHz. .......... 67
4.4 Timing diagram of $v_{out}$ of a Class-E Amplifier 27MHz. .......... 67
4.5 A common emitter Colpitts oscillator. ................................... 68
4.6 Timing diagram of $v_{in}$ of a Colpitts oscillator at 27MHz. ........ 69
4.7 Timing diagram of $v_{C1}$ of a Colpitts oscillator at 27MHz. ........ 69
4.8 Timing diagram of $v_{out}$ of a Colpitts oscillator at 27MHz. ........ 69
4.9 Block diagrams indicating separate power amplifier and oscillator blocks. 70
4.10 Block diagrams indicating combined power oscillator blocks. ........ 70
4.11 The Class-E oscillator [8]. ................................................. 71
4.12 The Class-E oscillator with a Hartley feedback network. ........ 72
4.13 Timing diagram of $v_{in}$ of the Class-E oscillator based on [8]. .... 73
4.14 Timing diagram of $v_{C1}$ of the Class-E oscillator based on [8]. .... 73
4.15 Timing diagram of $v_{out}$ of the Class-E oscillator based on [8]. .... 73
4.16 A 27MHz Class-E amplifier constructed in hardware, driven by a crystal oscillator. ................................................. 75
4.17 Schematic diagram of a Class-E oscillator with an LC feedback network and element between the transistors base and emitter terminals, being either a 100kΩ resistor or a Schottky diode. ............... 76
4.18 Schematic diagram of a Class-E oscillator with a 27MHz Crystal feedback network and element between the transistors base and emitter terminals, being either a 100kΩ resistor or a Zener diode. .......... 77
4.19 Schematic diagram of a Class-E oscillator with a 27MHz Crystal feedback network and element between the transistors base and emitter terminals, being either a 100kΩ resistor or a Zener diode. .......... 77
4.20 A small signal model of the Class-E self-oscillator of Figure 4.19 ... 81
4.21 Input signal of the Class-E Self-Oscillator of Figure 4.19 ............. 82
4.22 Voltage across $C_1$ in the Class-E Self-Oscillator of Figure 4.19 ... 83
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.23</td>
<td>Experimental set up with the transmission coil, lean beef, stacked spiral receiving coil and meat.</td>
<td>84</td>
</tr>
<tr>
<td>4.24</td>
<td>Voltage signal across the transmission coil of he Class-E self-oscillator of Figure 4.19</td>
<td>85</td>
</tr>
<tr>
<td>4.25</td>
<td>Voltage signal across the receiving coil after the biological tissue</td>
<td>85</td>
</tr>
<tr>
<td>5.1</td>
<td>A simulation of the $z$-component of the magnetic field pattern of a cylindrical helix coil. The scale ranges from $\pm 10,\text{A/m}$.</td>
<td>93</td>
</tr>
<tr>
<td>5.2</td>
<td>A simulation of the $z$-component of the magnetic field pattern of a planar Archimedean spiral coil. The scale ranges from $\pm 10,\text{A/m}$</td>
<td>93</td>
</tr>
<tr>
<td>5.3</td>
<td>A simulation of the $z$-component of the magnetic field pattern on the plane of a spiral. The scale ranges from $\pm 50,\text{A/m}$</td>
<td>96</td>
</tr>
<tr>
<td>5.4</td>
<td>A simulation of the $z$-component of the magnetic field pattern on the plane of four spirals covering the same area as that of Figure 5.3. The scale ranges from $\pm 50,\text{A/m}$</td>
<td>96</td>
</tr>
<tr>
<td>5.5</td>
<td>A simulation conducted on CST to determine the magnetic field patterns of an array of 20 spiral coils.</td>
<td>97</td>
</tr>
<tr>
<td>5.6</td>
<td>A sample pre-clinical testing scenario showing an enclosure, an array of spirals connected in series and parallel and a subject.</td>
<td>97</td>
</tr>
<tr>
<td>5.7</td>
<td>A screenshot of a one layer square spiral simulation.</td>
<td>100</td>
</tr>
<tr>
<td>5.8</td>
<td>Simulation results showing peak frequencies of the antenna shown in Figure 5.7 as the FR-4 substrate thickness varies.</td>
<td>101</td>
</tr>
<tr>
<td>5.9</td>
<td>Simulation results of the single layer spiral of Figure 5.7 showing peak frequencies as the relative permeability $\varepsilon_r$ is varied.</td>
<td>101</td>
</tr>
<tr>
<td>5.10</td>
<td>An image of a simulated four-layer spiral coil, comprising four coils covering 1.5mm x 1.5mm with 7-turns of 0.5mm thick conductors, separated by two 1.5mm FR-4 boards.</td>
<td>103</td>
</tr>
<tr>
<td>5.11</td>
<td>An image of the simulated four-layer spiral coil of Figure 5.10, with the FR-4 layer switched to transparent, allowing the conductors throughout the stacked-spiral to be visualised.</td>
<td>103</td>
</tr>
<tr>
<td>5.12</td>
<td>A simulation of the $z$-component of the magnetic field pattern of the single layer coil in Figure 5.7 at its SRF of 1.044GHz. The scale ranges from $\pm 10,\text{A/m}$.</td>
<td>103</td>
</tr>
<tr>
<td>5.13</td>
<td>A simulation of the $z$-component of the magnetic field pattern of the multi layer coil in Figure 5.10 at its SRF of 65MHz. The scale ranges from $\pm 10,\text{A/m}$.</td>
<td>103</td>
</tr>
<tr>
<td>5.14</td>
<td>A comparison between the simulated $\text{Re}(Z_{l,1})$ curves for a single square spiral, double layer spiral and a 4-layer stacked spiral.</td>
<td>103</td>
</tr>
<tr>
<td>5.15</td>
<td>A comparison between the simulated and measured results of the frequency vs real impedance $\text{Re}(Z_{l,1})$ plot.</td>
<td>106</td>
</tr>
<tr>
<td>5.16</td>
<td>A photograph of a four layer spiral coil.</td>
<td>107</td>
</tr>
</tbody>
</table>
5.17 A photo of the stacked spiral antenna receiving energy from a Class-E powered spiral array. ........................................... 107
5.18 Wireless power transfer with class-E amplifier. ....................... 108
5.19 Voltage signal across the Class-E transmitter .......................... 109
5.20 Voltage signal received on the stacked spiral antenna ............. 109
5.21 Spectrum of signal sent on the Class-E transmitter ................ 110
5.22 Spectrum of signal received on the stacked spiral antenna ........ 110
5.23 Rectified signal received from stacked spiral antenna .............. 111
6.1 The Class-E amplifier .................................................. 119
6.2 A low-power transmitter design using Class-E amplifier for PSK, FSK and OOK signals. ........................................... 121
6.3 A step response with damping ratios of 0.1 and 0.9 applying to the higher and lower curve respectively. .......................... 121
6.4 The effect of the damping factor $\zeta$ on efficiency $\eta$ with $R=500\Omega$, $V_{DD}=3V$, $l_{\text{channel}}=500\text{nm}$, $width_{p-channel}=20\mu m$, $width_{n-channel}=10\mu m$. 123
6.5 The effect of the load resistance $R$ on efficiency $\eta$ with a constant $\zeta$ of 0.1 and $V_{DD}$ of 3V and varying the scale of the MOSFET channel widths, $width_{p-channel}/width_{n-channel}$ while keeping the channel length 500nm. ............................................................... 123
6.6 Variations in $C_1$ and $C_2$ with $V_{DD}=3V$, $\zeta=0.1$, $R=500\Omega$, $L=982nH$, MOSFET channel length 500nm, $width_{p-channel}/width_{n-channel}=20\mu m/10\mu m$. a) The effect of varying $C_1$ while keeping a constant $C_2$ at 0.157pF. b) The effect of varying $C_2$ while keeping a constant $C_1$ at 0.157pF. 124
6.7 The effect of the supply voltage $V_{DD}$ on efficiency ($\eta$) with $R=500\Omega$, $\zeta=0.1$ ($C_1=C_2=0.157pF, L=982nH$), $l_{\text{channel}}(n,p)=500\text{nm}$, $width_{p-channel}=20\mu m$, $width_{n-channel}=10\mu m$. ............................... 125
6.8 A simulation plot of the output of the PSK circuit (403 MHz). ....... 126
6.9 A simulation plot of the output of the OOK modulated circuit. ....... 126
6.10 Output plot of an FSK time transient signal. .......................... 127
6.11 Frequency spectrum of Figure 6.10. .................................. 127
7.1 Block diagram showing the general architecture of implanted telemetry devices. ............................................................. 131
7.2 Square Wave ............................................................. 133
7.3 A practical square-wave including rise and fall times. .................. 134
7.4 A 27MHz square wave with 0.5 duty cycle and 1ps rise/fall times ... 135
7.5 Spectrum of square wave with 0.5 duty cycle of Figure 7.4 ........... 135
7.6 A 27MHz square wave with 0.174 duty cycle and 1ps rise/fall times ... 137
7.7 Spectrum of a square wave with 0.174 duty cycle of Figure 7.6 ....... 137
7.8 A Trapeze wave with 0.174 duty cycle and 4ns rise and fall time ... 138
List of Figures

7.9 Square wave with 0.174 duty cycle and 4ns rise and fall time of Figure 7.8 ................................................................. 138
7.10 System circuit diagram .................................................. 140
7.11 MICS-band antenna designed for operation in biological tissue .... 141
7.12 $|S_{1,1}|$ scattering parameter for the MICS-band antenna shown in Figure 7.11 when loaded with biological muscle tissue ........ 142
7.13 Data receiving coil optimised for 405MHz. Number of turns=6, $\Phi=7$mm, and wire thickness=1mm. ................................................ 143
7.14 Photo showing the experimental set up .................................. 144
7.15 Plots showing path loss vs beef thickness at 27MHz. Three curves indicate different thicknesses placed on the side of the receiving coil not facing the transmitter. The transmitted 8.36dB signal was provided by the Class-E self Oscillator from Chapter 4, and the signal was received on the implantable stacked spiral coil of Chapter 5 .................................. 145
7.16 Plot showing path loss vs beef thickness at 405MHz. The transmitted 8.36dB signal was provided by a signal generator sent on a MICS antenna and received on a wire wound coil optimised at 405MHz ..... 146
7.17 Output signal before the antenna ...................................... 147
7.18 Spectrum of the output before the antenna ......................... 148
7.19 Time diagram of the received 150kHz modulated signal with the 405MHz carrier signal after amplification and filtering ............ 150
7.20 Spectrum diagram of the received 150kHz modulated signal after amplification and filtering .......................................... 151
7.21 Example of a multi-user implantable telemetry systems .......... 153
A.1 A practical square-wave including rise and fall times .................. 167
List of Tables

2.1 Wireless power frequencies ........................................ 17
2.2 Data modulation schemes for implants ......................... 34
3.1 Measured power of two Class-E transmitter designs .......... 58
4.1 Comparisons between Class-E Circuits ....................... 78
7.1 Frequency bands with associated harmonics (MHz) .......... 154
7.2 Comparison of Telemetry Devices ............................. 154
Citations to Author’s Publications

The following published books were edited by the author of this dissertation.


Large portions of Chapter 3 have appeared in the following book chapters and conference paper respectively.


Chapter 4 was based on the following published conference and journal papers:


A significant part of Chapter 5 was based on the following journal and conference publications respectively.


Chapter 6 was based on the following publication:


The following publication presents the foundations for Chapter 7.


The journal publication below also relating to Chapter 7 has been sent for review prior to the submission of this dissertation.

A.N. Laskovski and M.R. Yuce, “A Medical Band Telemetry Link Inductively Powered in the ISM-Band at 27MHz”.

The provisional patent was submitted and approved in 2009 based on the concepts of Chapter 7, however it expired prior to the submission of this dissertation.

Acknowledgments

I would like to sincerely thank my supervisor Dr. Mehmet Yuce, who recognised my potential as a researcher. Beyond his generous investments in time, effort and resources, his guidance has been invaluable to my professional and personal development. His supervision truly gave meaning to the philosophical aspect in this Doctor of Philosophy program, and his contributions will never be forgotten. I would also like to thank my co-supervisor A/Prof. Gregg Suaning for being a part of my Ph.D and providing me with a great example of an interesting researcher to aspire to. I owe a special thanks to my friend and Ph.D colleague Michael Ho, who was very constructive and helpful throughout the program.

Throughout this Ph.D I have spent a considerable amount of time working in laboratories, and I would like to express my gratitude to the lab staff at the University of Newcastle. I would like to especially thank Nick Hawryluk for his friendly and useful help at the drop of a hat.

Undertaking a Ph.D has shown me the highs and lows of exploring new territory, and I can’t underestimate the value that my fellow Ph.D mates have added to my experience. The ability to encourage and de-stress one another, to share success and frustrations, or to simply know that there is a group of friendly faces in the common room that understands life as a Ph.D student, has made this experience very special. I have made friends from around the world with so much in common, and I look forward to keeping in touch as we disperse throughout the world exploring new fields.

Last but not least, I must acknowledge my incredibly supportive and loving family. I would like to thank my parents Jone and Snežana for providing me with the stability, encouragement and support to aim high and push beyond my comfort zone through
all levels of my education. I dearly thank my grandparents who have inspired me in different ways, from their relentless pioneering work ethics to their thirst for knowledge and education. Lastly I will thank my big sister Daniela, who has set such a positive example for me since I can remember. I am proud to say that I followed in her footsteps by undertaking this Ph.D.
To my family.