

Antennas, Waves, and Circuits
in
Radio Frequency Identification

David M. Hall

A thesis submitted for the degree of

Doctor of Philosophy

in

Electrical and Electronic Engineering
The University of Adelaide

September 2011

*“All truths are easy to understand once they are discovered
– the point is to discover them.”*

Galileo Galilei (1564-1642).

Contents

Abstract	viii
Statement of Originality	ix
Acknowledgments	x
Conventions	xi
Publications of the Author	xii
Abbreviations	xiv
List of Figures	xvii
List of Tables	xxii
Chapter 1. Introduction	1
1.1 Background	2
1.2 Outline of the thesis	2
1.3 Original contributions of the author	4
Chapter 2. UHF Planar Tags	6
2.1 Introduction	7
2.2 Read range	7
2.3 RFID antenna impedance	7
2.4 Calibrating the simulator	11
2.4.1 The Balanis dipole analysis	11
2.4.2 Loss calculation of a half-wave dipole	13
2.5 Shortening the antenna	15
2.6 Dipole with a loop	17
2.6.1 Modelling a book	21
2.7 Close-coupled tags	24
2.8 A two-port tag	28
2.9 Summary	34

Chapter 3. A Two-Part UHF Antenna	35
3.1 Introduction	36
3.2 Parts of the tag	37
3.2.1 The primary antenna	37
3.2.2 The secondary antenna	38
3.2.3 The completed tag	39
3.3 Tag testing	43
3.4 Summary	46
Chapter 4. A Combined UHF and HF Antenna	47
4.1 Introduction	48
4.2 An improved design	48
4.3 UHF layer	49
4.4 HF layer	50
4.5 Combined UHF and HF layers	50
4.6 RFID loop	52
4.7 The complete tag	52
4.8 RFID operation of the HF feature	54
4.9 RFID loop on the UHF layer	54
4.10 RFID loop on the HF layer	54
4.11 Summary	56
Chapter 5. DVD or CD Tag	57
5.1 Introduction	58
5.2 The disc tag antenna	59
5.3 Testing the tag	65
5.4 Summary	66
Chapter 6. Integrated Antenna Matching Network	67
6.1 Introduction	68
6.2 A small UHF loop	68
6.3 Testing the integrated matching network	72
6.4 Summary	73

Chapter 7. Increasing the UHF Field Near Metal	74
7.1 Introduction	75
7.2 Electromagnetic absorber material	75
7.3 Designing a tag for a metal surface	77
7.4 Fabricating a tag for a metal surface	78
7.5 Measurements on the absorber material	82
7.6 Summary	84
Chapter 8. A Drill String Identification Tag	85
8.1 Introduction	86
8.2 Construction of the test well	86
8.3 Construction of a drill string model	88
8.4 Construction of test coils	89
8.4.1 Impedance inside the well	89
8.4.2 Calculation of source voltage from coils	89
8.4.3 Power from coil in a magnetic field	92
8.5 Available source power	92
8.6 On-site noise measurements	95
8.6.1 Equipment used	95
8.6.2 Platform measurements	96
8.7 Available source power in octagon antenna field	98
8.8 Reduced depth of the well	100
8.9 Empirical results	103
8.9.1 Amount of detuning	103
8.9.2 Change of available source power	104
8.10 Design of a tag	104
8.11 Construction of a tag	105
8.12 Numerical analysis of a tag in a metal well	109
8.13 Summary	113
Chapter 9. Current Reference	114
9.1 Introduction	115
9.2 MOSFET operation in weak inversion	115
9.3 Circuit stability	115
9.4 Start-up circuit	117
9.5 Summary	121

Chapter 10. Random-Number Oscillator	122
10.1 Introduction	123
10.2 Designing an unstable oscillator	125
10.3 Clock extraction from the carrier	127
10.4 An unstable oscillator	129
10.5 An improved unstable oscillator	135
10.5.1 Long-term asynchronous oscillator stability	135
10.6 Summary	139
Chapter 11. HF Rectifiers	140
11.1 Introduction	141
11.2 Points to consider for rectifier design	141
11.3 The P-switch N-diode rectifier	142
11.3.1 The basic rectifier configuration	142
11.3.2 The CMOS realisation	143
11.3.3 Circuit operation	145
11.3.4 Reducing the gain of the parasitic vertical PNP	146
11.3.5 Explanation of guard rings	147
11.3.6 Placement of the elements	147
11.4 The N-diode N-diode rectifier	149
11.4.1 Layout considerations	152
11.5 Electrostatic discharge protection	153
11.5.1 Protecting the antenna terminals	153
11.6 The N-diode N-switch rectifier	156
11.7 Summary	157
Chapter 12. Passive Shunt Regulators	158
12.1 Introduction	159
12.2 Modulation detectors	159
12.2.1 The AM detector	159
12.2.2 The voltage comparator	160
12.2.3 Choosing the nominal current	160
12.2.4 A low-pass filter	161

12.2.5 A voltage-pulse-detect circuit	162
12.3 The regulator	162
12.4 Regulator design	166
12.4.1 Maximum-stress measurements	167
12.4.2 The basic shunt regulator	168
12.4.3 A lagging regulator with a capacitor	171
12.4.4 Step-input stability	172
12.4.5 A lagging regulator without a capacitor	173
12.5 Summary	175
Chapter 13. A Zero-Power On-Wafer Detector	176
13.1 Introduction	177
13.2 Circuit operation	178
13.3 Specific implementation	179
13.4 Verification of the circuit	180
13.5 Summary	183
Chapter 14. Conclusion	184
14.1 Introduction	185
14.2 Antennas	185
14.3 Waves	188
14.4 Circuits	189
14.5 Validation	192
14.6 Possible further work	192
Bibliography	193

Abstract

High-performance electronic labelling systems require the separate components to be designed in an optimum way and with a consideration of their interactions with other components in the system. As with many system designs many aspects of the electrical and electronic discipline must be pursued with skill for a successful design to emerge. In addition to dealing with these matters, the author considers low cost and long range along with manufacturability as key criteria for a high-performance labelling system and thus has kept these aspects in mind throughout the component design process.

The first part of the work describes the design of both near-field and far-field UHF antennas including a UHF antenna which is combined with an HF antenna. In a second part of the work are investigations of techniques for reading UHF tags on a metal surface and HF tags inside a hole formed in metal. Finally, the designs of low-power and low-cost microelectronic circuits for passive tags are discussed. Each system element designed by the author has been fabricated for successful empirical evaluation.

Statement of Originality

Name: _____

Program: _____

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution to David M. Hall 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.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library catalogue, the Australasian Digital Theses Program (ADTP) and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Signature: _____

Date: _____

Acknowledgments

The author would like to thank his supervisor Professor Peter H. Cole for his tireless support in the study for and writing of this thesis. Professor Cole has provided the author with insights into RFID unequalled in this field of study. He has also provided funds for fabrications and sustenance during many a long night in the laboratory.

The author would also like to thank the following persons in no order of importance.

Gordon Allison for his skills in the machine shop.

Said Alsarawi for help with layout tools, Op Amps, LaTeX, and UNIX.

Andrew Beaumont-Smith for help with layout tools and SPICE extraction.

Gareth Finch for luggage tag measurements.

Benno Flecker for book and fashion tag measurements.

Alf Grasso for VLSI fabrication.

Stephen Guest for general use of facilities.

Nathan Hu for help with LaTeX.

Ben Jamali for help with UNIX.

Kin Seong Leong for help around the laboratory.

Ian Linke for access to the workshop.

Philippe Martin for chip assembly.

Alastair McArthur for help with patents.

Ali Moini for help with VLSI tape out.

Mun Leng Ng for help around the laboratory and with LaTeX.

Damith Ranasinghe for help with MATLAB.

Conventions

This thesis was typeset using the L^AT_EX2e software.

Australian English spelling is adopted.

Plain style is used for the author's publications.

Harvard style is used for citation in this thesis.

SI units are used for physical units.

In schematics, transistor widths and lengths listed next to MOSFET symbols are in the order:

width

length

Publications of the Author

- [1] Peter H. Cole, David. M. Hall, Michael Y. Loukine and Clayton D. Werner, "Fundamental constraints on RFID tagging systems", Wireless Symposium, Santa Clara, CA, February, 1995
- [2] David M. Hall and Peter H. Cole, "A fully integrable turn-on circuit for RFID transponders", Wireless and Portable Design Conference, Burlington, MA, September, 1997
- [3] Greg Pope, Michael Y. Loukine, David M. Hall and Peter H. Cole, "Innovative systems design for 13.56 MHz RFID", Wireless and Portable Design Conference, Burlington, MA, September, 1997
- [4] Peter H. Cole and David. M. Hall, "Problems and solutions in multiple tag reading", Wireless and Portable Design Conference, Burlington, MA, September, 1997
- [5] D. C. Ranasinghe, D. M. Hall, P. H. Cole and D. W. Engels, "Embedded UHF RFID label antenna for tagging metallic objects", Proc. of the 2004 Intelligent Sensors, Sensor Networks & Information Processing Conference, Melbourne, Australia. pp. 343-347, 14-17 December, 2004
- [6] D. M. Hall, D. C. Ranasinghe, B. Jamali and P. H. Cole, "Turn-on circuits based on standard CMOS technology for active RFID labels" in VLSI Circuits and Systems II, edited by Jos Fco. Lpez, Francisco V. Fernandez, Jos Mara Lpez-Villegas, Jos M. de la Rosa, Proceedings of SPIE Vol. 5837, p. 310-320, Seville, Spain, June, 2005
- [7] M. L. Ng, K. S. Leong, D. M. Hall and P. H. Cole, "A small passive UHF RFID tag for livestock identification", IEEE 2005 International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications, Beijing, China, 8-12 August, 2005
- [8] Hall, David Malcolm, "Antenna", United States Design Patent USD630196S
- [9] Hall, David Malcolm, "Tag for data carrier", Australian Innovation Patent 2007100220
- [10] Murfett, David Bruce; Hall, David Malcolm, "A zero-power integrated circuit on-wafer detector", Australian Innovation Patent 2003100533
- [11] Martin, Philippe; Hall, David Malcolm, "Combined EAS/RFID tag", European Patent Application Publication EP2096582A1
- [12] Laviale, Anthony; Hall, David Malcolm, "Carton singulation process", Australian Patent Application 2007905992
- [13] Hall, David Malcolm, "Hook antenna", Australian Patent Application 2007100554
- [14] McArthur, Alastair Charles; Lousert, Christophe; Hall, David Malcolm; Lecire, Philippe, "RFID chimney", Australian Patent Application 2006906427
- [15] Hall, David Malcolm, "Adaptive kernel coupling to existing conductor", Australian Patent Application 2006904929
- [16] Hall, David Malcolm, "Reintroduction of carrier when communicating with electronic labels", Australian Patent Application 2006903385

-
- [17] Hall, David Malcolm, "UHF hook", Australian Patent Application 2006903384
- [18] Hall, David Malcolm; Pellet, Fabien; Tran, Tu, "Point of sale reading structure", Australian Patent Application 2006902193
- [19] Hall, David Malcolm, "Disc tag", Australian Patent Application 2006901289
- [20] Hall, David Malcolm, "Adaptive kernel coupling method", Australian Patent Application 2006900833
- [21] McArthur, Alastair Charles; Hall, David Malcolm; Simon, Elie; Lesluyes, Pierre, "Universal tag system", Australian Patent Application 2005906508
- [22] McArthur, Alastair Charles; Hall, David Malcolm, "Tunnel or cavity choke", Australian Patent Application 2005904458
- [23] Hall, David Malcolm, "Self-adjusting identification system", Australian Patent Application 2004905275
- [24] Hall, David Malcolm, "Integrated tag matching network", Australian Patent Application 2004905273
- [25] Hall, David Malcolm; D'Annunzio, Franck, "A method for the elimination of coupling nulls for items traversing an electro-magnetic field", Australian Patent Application 2003900700
- [26] Grasso, Alfio Roberto; Murfett, David Bruce; Hall, David Malcolm, "Method for avoiding collisions between rfid tags", Australian Patent Application 2003258380
- [27] Hall, David Malcolm, "Method and apparatus for maintaining pseudo-synchronism in rfid tags", Australian Patent Application 2003258379
- [28] Hall, David Malcolm, "Method for coding rfid tags", Australian Patent Application 2003215442
- [29] Hall, David Malcolm, "A method to reduce the far-field radiation of a magnetic loop for radio frequency identification systems", Australian Patent Application 2002953184
- [30] Grasso, Alfio Roberto; Murfett, David Bruce; Hall, David Malcolm, "Method of avoiding continued destructive tag collisions in a slotted ALOHA anti-collision scheme", Australian Patent Application 2002951699
- [31] Hall, David Malcolm, "Method of maintaining pseudo-synchronism with a finite length transmitted clock in electronic label systems", Australian Patent Application 2002951697
- [32] Hall, David Malcolm, "Reduction in the dynamic range of an electronic label's received signal", Australian Patent Application 2002951696
- [33] Grasso, Alfio Robert; Hall, David Malcolm, "Improvements in the reading of tags in ALOHA anti-collision schemes", Australian Patent Application 2002950886
- [34] Hall, David Malcolm; Cole, Peter Harold, "A system and method for interrogating electronic labels", Australian Patent Application 2002216836
- [35] Cole, Peter H.; Hall, David Malcolm; Turner, Leigh Holbrook; Kalinowski, Richard, "Electronic label reading system", Australian Patent Application 2001018451
- [36] Cole, Peter Harold; Hall, David Malcolm, "Object and document control system", Australian Patent Application 2000022709

Abbreviations

ABS	acrylonitrile butadiene styrene
AC	alternating current
Al	aluminium
ALOHA	an intermittent tag reply scheme
AM	amplitude modulation
AMI	American Microsystems Inc.
B	base
BNC	bayonet NeillConcelman
BW	bandwidth
C	capacitor or collector
CARP	carbon-amide reinforced plastic
CD	compact disc
CMOS	complementary metal-oxide semiconductor
Cu	copper
CW	continuous wave
D	drain
DC	direct current
DVD	digital versatile disc
EAS	electronic article surveillance
EEPROM	electrically erasable programmable read only memory
EIRP	equivalent isotropic power
EMC	electromagnetic compatibility
EMCO	EMCO Elektronik GmbH
EPC	electronic product code
ESD	electrostatic discharge
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FDTD	finite difference time domain
FM	frequency modulated
FR4	flame retardant 4 circuit board
G	gate
HF	high frequency
HFSS	high frequency structure simulator

HP	Hewlett Packard
ID	inside diameter
II	impact ionisation
ISD	Integrated Silicon Design
ISO	International Standards Organisation
L	inductor
LDD	lightly doped drain
MoM	method of moments
MOS	metal-oxide semiconductor
MOSFET	metal oxide field effect transistor
NMOS	N-type metal oxide semiconductor
NAND	not AND
NOR	not OR
NPN	N-type P-type N-type transistor
OD	outside diameter
OTA	operational transconductance amplifier
PCB	printed circuit board
PET	polyethylene terephthalate
PJM	phase jitter modulation
PM	phase modulation
PML	perfectly matched layer
PN	P-type N-type junction
PNP	P-type N-type P-type transistor
POR	power-on reset
ppm	parts per million
PTFE	polytetrafluoroethylene
PUR	polyurethane
PVC	polyvinyl chloride
Q	quality factor
r	series resistor
R	parallel resistor
RF	radio frequency
RFID	radio frequency identification
RRO	reply-rate oscillator
RTF	reader-talks-first
S	source
SD	standard deviation

SCR	silicon controlled rectifier
SEBS	styrene-ethylene/butylene-styrene
SKU	stock keeping unit
SMA	subminiature version A
SPICE	simulation program with integrated circuit emphasis
T	period
TE	transverse electric
TPE	thermoplastic elastomer
TPR	thermoplastic rubber
TPU	thermoplastic polyurethane
UHF	ultra high frequency
V_{DD}	positive supply node
VLSI	very large scale integration
V_{SS}	negative supply node
VSWR	voltage standing wave ratio
XOR	exclusive OR

List of Figures

2.1	Impinj Monza2 antenna impedance contour	9
2.2	NXP's reference antenna	9
2.3	NXP's reference antenna impedance	10
2.4	NXP's reference tag range	10
2.5	The basic antenna	17
2.6	The C-shaped antenna	18
2.7	3D antenna in 2D	19
2.8	A small 3-dimensional antenna	19
2.9	Untrimmed antenna	21
2.10	Simulated impedance of an antenna on a book	22
2.11	Read range of a book tag	23
2.12	Simulated impedance of a book antenna in air	24
2.13	Tag antenna parasitics	25
2.14	An antenna's influence on another	25
2.15	Read range of a stack of 5 tags 71 mm × 32 mm	27
2.16	Read range of a stack of 5 tags 50 mm × 30 mm	28
2.17	Mutual reactance of a pair of antennas	29
2.18	An omnidirectional antenna prototype	31
2.19	An omnidirectional antenna	32
2.20	An omnidirectional tag	32
2.21	Read range of an encapsulated omnidirectional tag	34

3.1	Primary antenna	38
3.2	Primary and secondary antennas	38
3.3	Primary and secondary antennas with alternative coupling	39
3.4	Primary antenna and alternative secondary antenna	39
3.5	Elements of a two-part tag	40

3.6	Elements of an alternative assembly	41
3.7	Mutual reactance between a pair of antennas	42
3.8	NXP book tag	43
3.9	Impinj book tag	43
3.10	Read range of a two-part NXP book tag	44
3.11	Read range of a two-part Impinj book tag	44
3.12	Antenna pattern of an NXP tag on a book	45
3.13	Antenna pattern of an NXP tag on PTFE	45

4.1	A combined UHF and HF tag	48
4.2	The UHF layer	50
4.3	The HF layer	51
4.4	HF layer on top of UHF layer	52
4.5	Separate RFID loop	53
4.6	The complete combined EAS and RFID tag	53
4.7	The RFID part integrated on the UHF layer	55
4.8	The RFID part integrated on the HF layer	55
4.9	The RFID part integrated alternatively on the HF layer.	56

5.1	Basic disc tag	60
5.2	Tag on disc	61
5.3	Alignment of disc and tag	62
5.4	Two discs on axis	62
5.5	Layers of a separate tag	63
5.6	Layers of an embedded tag	64
5.7	E-plane radiation pattern	64
5.8	Radiation pattern; stick-on tag; disc w/ extra metal	65
5.9	Arrangement of DVDs	66

6.1	Loop antenna with no matching	69
6.2	Loop antenna with an increased equivalent current path	70

6.3	Equivalent circuit of the matching network.	70
6.4	Smith chart showing matching procedure	71
6.5	Loop antenna with an integrated matching network	72

7.1	Return loss of absorbing material	77
7.2	Antenna impedance at 915 MHz in free space	79
7.3	Antenna impedance at 915 MHz 3.5 mm above metal	80
7.4	Antenna impedance at 915 MHz using absorber material	81
7.5	Metal mount tag antenna	82
7.6	Layers of the metal mount tag antenna	82

8.1	Deep brass well, 25.5 mm depth	87
8.2	Drill string model	88
8.3	Equivalent circuit of coil	89
8.4	Single-turn test coils	90
8.5	Impedance, coil without legs, deep well	91
8.6	Dynamic impedance, coil without legs, deep well	91
8.7	Impedance, coil with legs, deep well	92
8.8	Dynamic impedance, coil with legs, deep well	93
8.9	Drill string model in square loop antenna	93
8.10	Position of receiving antenna under the platform	95
8.11	Measured noise spectrum: 30 MHz BW	96
8.12	Measured noise spectrum: 5 MHz BW	97
8.13	Measured noise spectrum: 1 MHz BW	97
8.14	Larger diameter octagon antenna	98
8.15	Octagon antenna return loss	99
8.16	Shallow brass well, 18 mm depth	100
8.17	Impedance, coil without legs, shallow well	101
8.18	Dynamic impedance, test coil without legs, shallow well	102
8.19	Impedance, coil with legs, shallow well	102
8.20	Dynamic impedance, coil with legs, shallow well	103

8.21	Simulation calibration of 1-turn coils	106
8.22	Addition of fixed capacitance to 1-turn coils	107
8.23	Simulation of 4-turn coils	108
8.24	Model of ferrite coil	110
8.25	Model of ferrite coil in brass well	110
8.26	Well entry represented as a radiation surface	111
8.27	Start and finish tuning points as the well wears	112

9.1	Current reference	116
9.2	Unstable current reference	117
9.3	Stable current reference	118
9.4	Start-up circuit	119
9.5	Current reference with slaves	120
9.6	Split resistor	121

10.1	Random number from a noise source	124
10.2	Digital mixer used for random data	125
10.3	Pseudo NMOS inverter for clock extraction	127
10.4	Branch-based logic divide-by-2 circuit	128
10.5	Transistor level XOR gate	130
10.6	A NOR gate	130
10.7	Unstable oscillator with shared reference	133
10.8	Unstable oscillator shared reference results	134
10.9	Unstable oscillator with separate references	136
10.10	Unstable oscillator separate references results	137
10.11	Long-term stability	138

11.1	Symbolic circuit diagram of a CMOS rectifier	143
11.2	P-switch N-diode rectifier	144
11.3	P-switch N-diode rectifier major parasitics	144
11.4	Guard rings in an N-well process	148

11.5	Parasitics and guard rings	149
11.6	Parasitics and guard rings with separation	150
11.7	Parasitics and guard rings with isolation well	151
11.8	N-diode N-diode rectifier	152
11.9	ESD protection	154
11.10	ESD protection with gate bouncing	155
11.11	N-diode N-switch rectifier	156
<hr/>		
12.1	The voltage-pulse-detect circuit	163
12.2	The basic shunt regulator	164
12.3	Layout of the basic shunt regulator	169
12.4	Regulator with a capacitor storage node	171
12.5	Regulator with no storage capacitor	174
<hr/>		
13.1	General wafer detect schematic	177
13.2	Detailed wafer detect schematic	179
13.3	Loop connected	181
13.4	Loop opened	181
13.5	LOOPA shorted to V_{SS}	182
13.6	LOOPB shorted to V_{SS}	182
13.7	LOOPA and LOOPB shorted to V_{SS}	183

List of Tables

2.1	Impinj Monza2 antenna impedance	8
2.2	NXP Ucode G2XM chip data	8
2.3	Impedance results for a 61 segment dipole	13
2.4	Dielectric constants	23
2.5	Measured material losses	30
2.6	Measured TPU losses	31
8.1	Power measurements, single-turn solenoid, deep well	94
8.2	Receiving antenna factors	96
8.3	Power measurements, single-turn solenoid, deep well	99
8.4	Power measurements, single-turn solenoid, shallow well	103
8.5	Material parameters used for simulation.	109
8.6	Modelled ferrite core.	111
10.1	Comparison of XOR and NOR gates	131