

LOW-VOLTAGE CURRENT-MODE ANALOG CIRCUIT STRUCTURES AND THEIR APPLICATIONS

By

S.S. RAJPUT

Department of Electrical Engineering

Submitted

**in fulfillment of the requirements of the Degree of
Doctor of Philosophy**

to the

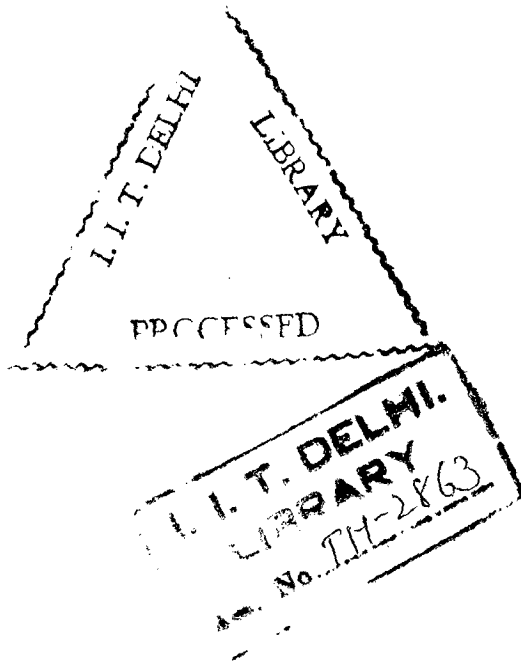


Indian Institute of Technology, Delhi

August, 2001

integrated circuit

TM
621.382.2/3
RAJ-L



CERTIFICATE

This is to certify that the thesis entitled, “**LOW-VOLTAGE CURRENT-MODE ANALOG CIRCUIT STRUCTURES AND THEIR APPLICATIONS**”, being submitted by Mr. S. S. Rajput to the Indian Institute of Technology, Delhi, for the award of the degree of ‘Doctor of Philosophy’ in the Department of Electrical Engineering, is a record of bonafide research work carried out by him.

Mr. S. S. Rajput has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard.

The results contained in this work have not been submitted in part or full, to any other University or Institute for the award of any degree.



(Professor S. S. Jamuar)

Department of Electrical Engineering

Indian Institute of Technology, Delhi

Hauz Khas, New Delhi –110016

INDIA

DEDICATED
TO
MY FATHER SRI NATTHU SINGH
&
MY MOTHER SMT. BISNO DEVI

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to a number of people who supported me during my work on this thesis which would not have been possible – at least not on this level –without their kind help.

My first words of gratitude go to my esteemed supervisor, Prof. S. S. Jamuar, whose stimulated guidance, perennial encouragement, unwavering support and unceasing enthusiasm were crucial for the completion of this work. This thesis in this shape could have been possible due to invaluable suggestions, keen interest, direction and active help of Prof. Jamuar, inspite of his busy schedule.

I express my gratitude to my teacher, Prof. S. C. Dutta Roy, who introduced the world of digital signal processing to me. He reviewed my papers at a very short notice and gave many invaluable suggestions.

I record my appreciation for Prof. Surendra Prasad and Prof. R. K. Patney for their keen interest in my work. They have helped me at several occasions.

I wish to thank Dr. B. S. Panwar, Prof. G. S. Vishwesaran, Prof. C. P. Ravikumar and Prof. V. C. Prasad members of student research committee. They have given number of new ideas to improve the work and helped me whenever approached.

Special thanks are due to Prof. Vinod Chandra, Dr. M. Jagdesh Kumar, Dr. B. Bhowmik. They taught me the subjects, which were the part of academic curriculum and were crucial for the completion of this thesis.

I thank Dr. R. Bhattacharyya, Head, Thin Film Technology Group for his help and cooperation without which this work may not have been completed.

I sincerely convey my thanks to all my colleagues, specially Mr. C. M. S. Rauthan, Dr. K. M. K. Srivatsa, Dr. P. N. Dixit, Dr. B. S. Verma, Dr. O. S. Panwar, Dr.

Susheel Kumar, Dr. Sudheer Kumar, Dr. Rajnish Sharma and Mr. Shashank Sharma, members of Thin Film Technology Group, National Physical Laboratory, New Delhi.

The help and encouragement given by my friends specially Dr. Rajeev Chopra, Mr. Anil Kumar, Mr. P. S. Negi, Dr. C. P. Sharma, Dr. S. S. Bawa, Dr. T. K. Saxena, Dr. P. K. Aswini Kumar, Mr. Chandra Kant, Mr. Mahaveer Singh, Dr. B. C. Arya and Dr. T. D. Senguttuvan require great appreciation.

The help rendered by my friend Dr. K. K. Saini is matchless and is gratefully acknowledged.

It is my rare privilege to express my gratitude to my teacher, Prof. J. P. Gupta, former Dean, University of Roorkee, ROORKEE (Now IIT Roorkee), former member secretary, All India Council of Technical Education, former Head, IT group and Dean, Indian Institute of Information Technology and Management (IITM), Gwalior, and currently Director, Jay Pee Institute of Information Technology, Noida, UP. His encouragement always remains an inspiration for me. His special interest in my work and me is highly appreciated.

I have immense pleasure to acknowledge my dearest son Ahlad Kumar and my wife Manju Rajput for their untiring efforts and devotion towards this work. I cannot forget the patience that they have showed during the course of this study. Without their help and encouragement it may not have been possible to complete this work.

I am grateful to the Head, Department of Electrical Engineering, IIT, Delhi, for having supported this work. I also thank all my other colleagues at IIT, Delhi.

I am very grateful to Director NPL for supporting me during the course of this study.



(S. S. Rajput)

ABSTRACT

Low-voltage and low-power mixed mode circuit design has gained importance in recent time due to the advent of portable electronic system and mobile communication system. The present investigation is primarily concerned with the study and design of low-voltage, low-power circuits and their applications in linear and nonlinear circuit design. Current-mode design techniques, which offer voltage independent high bandwidth analog circuits, have been used to design three new low-voltage high performance current mirrors (LVCMs) in the present study. Using these LVCMs, four voltage buffer (VB) structures have been designed. Adaptive biasing technique has been introduced to enhance the input current range, decrease the input compliance and reduce the undesirable offset current in the LVCM. To increase the LVCM bandwidth, resistive and capacitive compensations have also been used. Resultant LVCMs have input currents in the range of 1 μA to 500 μA with a bandwidth of 2.5 GHz. These voltage buffers have near rail-to-rail input output voltage swings and a bandwidth of approximately 500 MHz. These LVCMs and VBs use ± 1.0 V power supply. Sensitivity and temperature analysis have been carried out for these proposed structures.

Analog signal processing cells like current conveyors (CCs), current feedback amplifiers (CFAs), operational floating amplifiers (OFAs) etc., are the current mode replacements of operational amplifiers. The LVCMs and VBs have been used in the design of new low-voltage analog signal processing (ASP) cells and eight new structures operating at ± 1.0 V for CCII, one CCI and one CCIII have been proposed. These

structures have a bandwidth of 200 MHz. Two CFA structures, which use CCII as basic cells, have also been designed. All these structures operate at ± 1.0 V supply voltage and have a bandwidth of approximately 120 MHz. Two OFC structures have also been obtained by suitably modifying the CCII structures. The use of OFCs in development of current amplifiers, voltage amplifiers has been demonstrated. Finally some linear and nonlinear applications of the ASP cells are demonstrated. They include current amplifiers, voltage amplifiers, current square rooter, current squarer, wave shaping circuits and log and anti-log amplifiers. The current sensing capability has been used to demonstrate the use of CCs in built-in self-test structures. ASP cells have also been used in some special type of linear as well as non-linear applications like exponential current source, current electrometers and space plasma simulations.

The proposed design could not be realized in silicon owing to non-availability of foundry facility at the place of study. All the results presented in this investigation are based on the P-Spice simulations using level 3 model parameters for 0.8-micron CMOS technology. These results match the theoretical predictions.

CONTENTS

	Page No.
CERTIFICATE	i
ACKNOWLEDGEMENTS	iii
ABSTRACT	v
CONTENTS	vii
LIST OF FIGURES	xii
LIST OF TABLES	xix
NOMENCLATURE	xx
CHAPTER 1 INTRODUCTION	1-26
1.1 Need for current-mode circuits	3
1.2 Critical issues	12
1.3 Current-mode low-voltage design	14
1.3.1 Using sub-threshold technique	15
1.3.2 Bulk-driven MOSFETs	17
1.3.3 Self-cascode technique	18
1.3.4 Using floating gate MOSFETs	21
1.3.5 Level shifter technique	23
1.4 Statement of the problem	25
1.5 Outline of the thesis	26
CHAPTER 2 NEW ANALOG CELLS	29-93
2.1 Introduction	29
2.1.1 Current mirrors	30
2.1.2 Current output stage	31
2.1.3 Voltage buffers	32

2.2	Low-voltage current mirrors	34
2.2.1	Low-voltage current mirror Type 1	34
2.2.1.1	Circuit structure	34
2.2.1.2	Operation in sub-threshold region	35
2.2.1.3	Proposed LVCM structure	35
2.2.1.4	Adaptive biasing technique	38
2.2.1.5	Compensation technique	41
2.2.1.6	Circuit modeling and frequency enhancement	41
2.2.1.7	Sensitivity analysis	43
2.2.1.8	Temperature dependence	45
2.2.1.9	Simulation results for LVCM	46
2.2.1.10	Simulation results for ABLVCM	49
2.2.2	Low-voltage current mirror Type 2	52
2.2.2.1	M3 in saturation region	52
2.2.2.2	M3 in sub-threshold region	54
2.2.2.3	Adaptive biasing	55
2.2.2.4	Compensation techniques	56
2.2.2.5	Circuit analysis	58
2.2.2.6	Temperature effects	58
2.2.2.7	Simulation results	59
2.2.3	Low-voltage current mirror Type 3	63
2.2.3.1	LVCM structure	63
2.2.3.2	Low-voltage composite output current mirror	65
2.2.3.3	CM modeling	66
2.2.3.4	Frequency response	67
2.2.3.5	Sensitivity analysis	67
2.2.3.6	Simulation results	68
2.3	Low-voltage current output stage	72
2.3.1	Circuit architecture	72
2.3.2	Simulation results	75

2.4	Low-voltage voltage buffers	78
2.4.1	Voltage buffer Type 1	78
2.4.2	Voltage buffer Type 2	81
2.4.3	Voltage buffer Type 3	85
2.4.4	Voltage buffer Type 4	88
2.5	Conclusion	91

CHAPTER 3 SIGNAL PROCESSING CELLS 93-142

3.1	Introduction	94
3.2	Current conveyors	95
3.2.1	CCI realization	98
3.2.2	CCII realization	103
3.2.2.1	Class A CCII realization	103
3.2.2.2	Class AB CCII realization	108
3.2.3	Other CCII structures	113
3.2.4	CCIII realization	116
3.3	Current-mode amplifiers	120
3.3.1	Low-voltage $V-I$ converter	120
3.3.2	Current mirror op amp	122
3.3.3	Current feedback amplifiers	126
3.3.3.1	CFA Type 1	127
3.3.3.2	CFA Type 2	131
3.3.4	Operational floating conveyors	133
3.3.4.1	Class A OFC	133
3.3.4.2	Class AB OFC	139
3.4	Conclusion	141

CHAPTER 4 SIGNAL PROCESSING APPLICATIONS 143-175

4.1	Introduction	143
4.2	Linear applications	144
4.2.1	CC based amplifiers	144
4.2.1.1	Voltage amplifier	144
4.2.1.2	Current amplifier	147

4.2.2	CCII based trans-conductor	149
4.2.3	CFA based notch filter	151
4.3	Nonlinear applications	153
4.3.1	CCII based current multiplier	154
4.3.2	Squarer /square rooter cell	161
4.3.2.1	Square rooting structure	162
4.3.2.2	Current squaring structure	164
4.3.3	CCII based diode wave shaper	166
4.3.4	CMOA based zero crossing detector	170
4.3.5	LVCM based absolute value converter	172
4.4	Conclusion	174
CHAPTER 5 SPECIAL ASP APPLICATIONS		176-201
5.1	Introduction	176
5.2	CCs as current sensing device	179
5.2.1	CCII as current sensors	179
5.2.2	CCIII as current sensors	183
5.3	Current electrometer	185
5.4	Exponential current source	191
5.5	Electronic simulation of plasma	193
5.5.1	BiCMOS plasma simulator	194
5.5.2	CMOS Plasma simulator	197
5.6	Conclusion	200
CHAPTER 6 CONCLUSIONS AND SUGGESTIONS		202-208
FOR FURTHER WORK		
6.1	Introduction	202
6.2	Summary of contributions	204
6.3	Suggestions for further work and study	207

REFERENCES	209-218
APPENDIX A SPICE MODEL PARAMETERS	219-220
APPENDIX B INPUT VOLTAGE CALCULATIONS	221-225
B.1 Introduction	221
B.2 M1 and M3 operating in sub-threshold region	222
B.3 M1 operating in saturation and M3 operating in sub-threshold region	223
B.4 M1 and M3 operating in saturation region	224
B.5 M1 operating in linear region and M3 operating in saturation region	225
APPENDIX C OFFSET CURRENT CALCULATION	226-228
C.1 Introduction	226
C.2 M3 operating in sub-threshold region	226
C.3 M3 operating in saturation region	227
APPENDIX D AC ANALYSIS OF PROPOSED LOW-VOLTAGE CURRENT MIRRORS	229 -239
D. 1 Modeling of Current Mirrors	229
D.2 Sub-threshold operation of MOSFETs	230
D.3 Low Frequency analysis	231
D.4 High frequency analysis	234
D.5 LVCM type 3	237
APPENDIX E NOTCH FILTER ANALYSIS	240 -242
APPENDIX F PROPOSED CIRCUIT FOR MATHEMAICAL OPERATIONS	243-245
LIST OF PUBLICATION	246-247
BIOGRAPHICAL PROFILE OF RESEARCHER	248