Signal Generation and Detection for Microwave Photonic Radar Systems

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by

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Certificate

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I hereby certify that the work which is being presented in the thesis entitled **"Signal Generation and Detection for Microwave Photonic Radar Systems"** in the fulfillment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY** and submitted in the **Department of Electrical Engineering, Indian Institute of Technology Delhi**, is an authentic record of my own work carried out during the time period from December 2018 to November 2023 under the supervision of Prof. Amol Choudhary, Assistant Professor, Department of Electrical Engineering, Indian Institute of Technology Delhi, India.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute and any collaboration with other students with their contributions has been clearly highlighted. Any work that has been published is mentioned under the "List of Publications" on page vii.

Rajveer Dhawan

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Abstract

Linear frequency modulated (LFM) signals are widely employed in modern radar systems due to their significant time-bandwidth product and inherent pulse compression capability. Conventional radar entails the use of electronic methods for signal generation and processing. However, these methods face significant challenges due to their limited bandwidth, restricted functionality, high jitter, slow processing speed, and inadequate resolution. To address these problems, photonics-based radar technologies have been proposed to overcome the bottleneck of electronics for microwave generation and processing. Photonic technologies offer unique characteristics, which include wide bandwidth signal generation, processing, low jitters, low-loss transmission, immunity to electromagnetic interference (EMI), and compatibility with radio-over-fiber technology. The primary objective of this approach is to leverage the benefits of photonic technologies for the purpose of generating, processing, controlling, and distributing microwave waveforms enabling intricate functionalities that cannot be directly executed in the RF domain.

The primary focus of the research in this thesis is based on the LFM signal generation, processing, and detection utilising a dual-drive Mach Zehnder modulator (DDMZM), which offers a significant level of flexibility and ease of use due to the presence of only a single DC bias. The thesis investigates various aspects of microwave photonic radar, such as MWP link design for signal generation showing dual and cross chirp generation in two different frequency bands, ultra-wideband and frequency-agile waveform generation, photonic signal processing, range processing, velocity estimation and performance evaluation of FMCW radars in lab environment. The experimental validation of the radar system's shows the potential of its capabilities in real-world scenarios. Additionally, the thesis discusses the limitations of microwave photonic radar and proposes future research directions to overcome these challenges and explore new opportunities for its advancement.

सार

रैखिक आवृत्ति संग्राहक (एलएफएम) सिग्नल अपने महत्वपूर्ण समय-बैंडविड्थ उत्पाद और अंतर्निहित पल्स संपीड़न क्षमता के कारण आधुनिक रडार प्रणालियों में व्यापक रूप से नियोजित होते हैं। पारंपरिक रडार में सिग्नल उत्पादन और प्रसंस्करण के लिए इलेक्ट्रॉनिक तरीकों का उपयोग शामिल है। हालाँकि, इन विधियों को उनकी सीमित बैंडविड्थ, प्रतिबंधित कार्यक्षमता, उच्च घबराहट, धीमी प्रसंस्करण गति और अपर्याप्त रिज़ॉल्यूशन के कारण महत्वपूर्ण चुनौतियों का सामना करना पड़ता है। इन समस्याओं के समाधान के लिए, माइक्रोवेव उत्पादन और प्रसंस्करण के लिए इलेक्ट्रॉनिक्स की बाधाओं को दूर करने के लिए फोटोनिक्स-आधारित रडार प्रौद्योगिकियों का प्रस्ताव किया गया है। फोटोनिक प्रौद्योगिकियां अद्वितीय विशेषताएं प्रदान करती हैं, जिसमें व्यापक बैंडविड्थ सिग्नल पीढ़ी, प्रसंस्करण, कम झटके, कम-नुकसान संचरण, विद्युत चुम्बकीय हस्तक्षेप (ईएमआई) के प्रति प्रतिरक्षा और रेडियो-ओवर-फाइबर प्रौद्योगिकी के साथ संगतता शामिल है। इस दृष्टिकोण का प्राथमिक उद्देश्य जटिल कार्यात्मकताओं को सक्षम करने वाले माइक्रोवेव तरंगों को उत्पन्न करने, प्रसंस्करण, नियंत्रित करने और वितरित करने के उद्देश्य से फोटोनिक प्रौद्योगिकियों के लाभों का लाभ उठाना है जिन्हें सीधे आरएफ डोमेन में निष्पादित नहीं किया जा सकता है।

इस थीसिस में शोध का प्राथमिक फोकस एलएफएम सिग्नल जेनरेशन, प्रोसेसिंग और डुअल-ड्राइव मैक ज़ेन्डर मॉड्यूलेटर (डीडीएमजेडएम) का उपयोग करके पता लगाने पर आधारित है, जो केवल की उपस्थिति के कारण लचीलेपन और उपयोग में आसानी का एक महत्वपूर्ण स्तर प्रदान करता है। एकल डीसी पूर्वाग्रह. थीसिस माइक्रोवेव फोटोनिक रडार के विभिन्न पहलुओं की जांच करती है, जैसे सिग्नल जेनरेशन के लिए एमडब्ल्यूपी लिंक डिजाइन, दो अलग-अलग फ्रीक्वेंसी बैंड में दोहरी और क्रॉस चिरप जेनरेशन, अल्ट्रा-वाइडबैंड और फ्रीक्वेंसी-एजाइल वेवफॉर्म जेनरेशन, फोटोनिक सिग्नल प्रोसेसिंग, रेंज प्रोसेसिंग, वेग अनुमान और प्रयोगशाला वातावरण में FMCW राडार का प्रदर्शन मूल्यांकन। रडार प्रणाली का प्रायोगिक सत्यापन वास्तविक दुनिया के परिदृश्यों में इसकी क्षमताओं की क्षमता को दर्शाता है। इसके अतिरिक्त, थीसिस माइक्रोवेव फोटोनिक रडार की सीमाओं पर चर्चा करती है और इन चुनौतियों को दूर करने और इसकी उन्नति के लिए नए अवसरों का पता लगाने के लिए भविष्य के अनुसंधान दिशाओं का प्रस्ताव करती है।

List of Publications

Patents

[P1] Amol Choudhary, **Rajveer Dhawan**, Reena Parihar, “Photonic Generation of Multiband Dual or Cross LFM Waveform with Bandwidth Doubling using a single Dual-Drive Mach-Zehnder Modulator,” Indian Patent No. 202211010851, Feb2022 (filed).

[P2] Amol Choudhary, **Rajveer Dhawan**, Reena Parihar, Mukund Jha, “Tunable Microwave Photonic Bandpass Filter using the Mach Zehnder Interferometer and Stimulated Brillouin Scattering,” Indian Patent No. 202211010792, Feb2022 (filed).

Contributions to peer-reviewed journals contributing to the thesis.

[J1] **R. Dhawan** and A. Choudhary, “Photonic Generation of Coded Nonlinear Frequency Modulated RADAR Waveforms,” Results in Optics 13, 100583 (2023), doi: 10.1016/j.rio.2023.100583 .

[J2] **R. Dhawan,** D. Parida, R. Parihar, M. Jha, and A. Choudhary, “Multiband LFM waveform generation and band-selection using stimulated Brillouin scattering,” Appl. Opt. 62, 6737-6745 (2023), doi:10.1364/AO.495397.

[J3] **R. Dhawan**, K. Moyal and A. Choudhary, “Optical Filter-less Photonic FMCW Radar for Multi-target Detection,” IEEE Photonics Technology Letters 35(2), 81-84 (2023), doi: 10.1109/LPT.2022.3224219.

[J4] **R. Dhawan**, R. Parihar and A. Choudhary, “Multiband Dual and Cross LFM Waveform Generation Using a Dual Drive Mach Zehnder Modulator,” Optics Communications, 129144 (2022), doi:10.1016/j.optcom.2022.129144.

Contributions to other peer-reviewed journals

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[J6] M. Jha, **R. Dhawan**, R. Parihar and A. Choudhary, “Highly Flexible RF Filter Responses using Stimulated Brillouin Scattering with bandwidth up to 1 GHz,” Journal of Lightwave Technology 41(21), 6675-6683 (2023), doi: 10.1109/JLT.2023.3293798.

[J7] M. Jha, **R. Dhawan**, R. Parihar and A. Choudhary, “Frequency Response Tailoring of a Phase Modulated Link With Stimulated Brillouin Scattering,” IEEE Photonics Technology Letters 34(19), 1054-1057 (2022), doi: 10.1109/LPT.2022.3199586.

[J8] R. Parihar, **R. Dhawan**, S. Goel, B. O. Subham and A. Choudhary, “Design of Microwave Photonic Subsystems Using Brillouin Scattering,” Journal of Lightwave Technology 39(4), 977-991 (2021), doi: 10.1109/JLT.2020.3045629.

[J9] P. Raj, R. Parihar, **R. Dhawan**, and A. Choudhary, “Energy-efficient bandwidth enhancement of Brillouin microwave photonic bandpass filters,” Opt. Express 30, 30739-30749 (2022), doi: 10.1364/OE.465813

[J10] H. J. Pandit, A. Tyagi, H. Vaid, **R. Dhawan,** and A. Choudhary, “Single sideband modulation formats for quantum atom interferometry with Rb atoms,” Appl. Phys. B 129, 24 (2023), doi: 10.1007/s00340-022-07961-1.

Manuscripts submitted to peer-reviewed journals and under preparation

[S1] **R. Dhawan,** G. Singh, A. Dixit, and A. Choudhary, “Fiber-powered Antenna for 2-Way Communications Using RF Over Fiber,” (under preparation).

Contributions to peer-reviewed conferences contributing to the thesis.

[C1] **R. Dhawan**, D. Parida, and A. Choudhary, “Photonic Generation and Band-selection of Multi-Carrier Chirped Waveforms through Stimulated Brillouin Scattering,” 2023 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC), Munich, Germany, 1-1 (2023)

[C2] **R. Dhawan** and A. Choudhary, “Photonic Generation of Nonlinear 13-bit Barker-Coded Frequency Modulated Radar Waveforms,” Photonics-2023, IISC Bangalore.

[C3] **R. Dhawan**, R. Parihar and A. Choudhary, “Photonic Generation of Multiband V and Cross Chirps using a Dual-Drive Mach Zehnder Modulator,” in 2023 National Conference on Communications, Guwahati, India, 1-5 (2023), doi: 10.1109/NCC56989.2023.10067902.

[C4] **R. Dhawan**, R. Parihar, A. Choudhary, “Photonic Generation of Multi-Carrier Chirped Waveform using a Dual-Drive Mach Zehnder Modulator,” in Proceedings of the 2022 Conference on Lasers and Electro-Optics Pacific Rim, Technical Digest Series (Optica Publishing Group, 2022), paper P_CM18_01.

[C5] **R. Dhawan**, K. Moyal, and A. Choudhary, "Multi-target Detection with an Optical Filter-less Photonic FMCW Radar," in Frontiers in Optics + Laser Science 2022 (FIO, LS), Technical Digest Series (Optica Publishing Group, 2022), paper JW4B.32.

[C6] D. Parida, **R. Dhawan**, and A. Choudhary, "Dual-chirp Waveforms with Optical Filter-less Photonic Dechirping for Distance and Velocity Measurement in FMCW RADARs," in Conference on Lasers and Electro-Optics/Europe (CLEO/Europe 2023) and European Quantum Electronics Conference (EQEC 2023), Technical Digest Series (Optica Publishing Group, 2023), paper ci_7_6.

[C7] K. Moyal, **R. Dhawan**, A. Choudhary, "Optical Filter-less Photonic Dechirping of a Frequency-Modulated Continuous-Wave Radar," in Proceedings of the 2022 Conference on Lasers and Electro-Optics Pacific Rim, Technical Digest Series (Optica Publishing Group, 2022), paper P_CM18_02.

Contributions to other peer-reviewed conferences

[C8] R. Parihar, **R. Dhawan**, and A. Choudhary, "Optimised Microwave Phase Shifter using Brillouin-Induced Low Biasing," in Conference on Lasers and Electro-Optics/Europe (CLEO/Europe 2023) and European Quantum Electronics Conference (EQEC 2023), Technical Digest Series (Optica Publishing Group, 2023), paper cd_12_4.

[C9] G. Singh, **R. Dhawan**, A. Dixit, A. Choudhary, "Fiber-powered Antenna Using RF Over Fiber for 2-Way Communications," in Frontiers in Optics + Laser Science 2022 (FIO, LS), Technical Digest Series (Optica Publishing Group, 2022), paper JTu5B.65.

[C10] M. Jha, R. Parihar, **R. Dhawan**, and A. Choudhary, "Stimulated Brillouin Scattering based Switchable EIA and EIT filter in a Phase Modulated Link," in Conference on Lasers and Electro-Optics/Europe (CLEO/Europe 2023) and European Quantum Electronics Conference (EQEC 2023), Technical Digest Series (Optica Publishing Group, 2023), paper cd_12_3.

[C11] P. Raj, R. Parihar, **R. Dhawan**, and A. Choudhary, "Low-power Bandwidth Enhancement of Brillouin Microwave Photonic Filters using RF Interferometry," in Frontiers in Optics + Laser Science 2022 (FIO, LS), Technical Digest Series (Optica Publishing Group, 2022), paper FM4D.3.

[C12] M. Jha, R. Parihar, **R. Dhawan**, and A. Choudhary, "Stimulated Brillouin Scattering based Null compensation in a Phase Modulated Link," in Frontiers in Optics + Laser Science 2022 (FIO, LS), Technical Digest Series (Optica Publishing Group, 2022), paper JTu5A.46.

[C13] A. Tyagi, H. J. Pandit, **R. Dhawan**, and A. Choudhary, "Single Sideband Modulation Formats for Quantum Atom Interferometry with Rb Atoms," in Frontiers in Optics + Laser Science 2022 (FIO, LS), Technical Digest Series (Optica Publishing Group, 2022), paper JW4B.27.

Table of Contents

List of Figures

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

List of Tables

List of Acronyms

A

ADC	Analog-to-Digital Converters
APL	Analog Photonic Link
AF	Ambiguity Function
AWG	Arbitrary Waveform Generator

B

BT	Bias Tee
BW	Bandwidth

C

CW	Continuous Waveforms

D

dB	Decible
DDS	Direct Digital Synthesizers
DDMZM	Dual Drive Mach Zehnder Modulator
DPMZM	Dual-Parallel-Mach-Zehnder-Modulator
DP-DPMZM	Dual-Polarization-Dual-parallel-Mach-Zehnder-Modulator
DFB	Distributed Feedback Laser

E

EMI	Electromagnetic Interference
EOM	Electro-optic Modulators
ESA	Electrical Spectrum Analyser
E/O	Electrical to Optical

F

FBG	Fiber Bragg Gratings
FMCW	Frequency Modulated Continuous Wave
FOPEN	Foliage Penetrating
FWHM	Full-Width Half Maxima

G

GHz	Giga Hertz

I

ITU	International Telecommunication Union
IM	Intensity Modulation
IMDD	Intensity Modulated Direct Detection
ISAR	Inverse Synthetic Aperture Radar

L

LD	Laser Diode
LFM	Linear Frequency Modulated
LSB	Lower Sideband

M

MaTP	Maximum Transmission Point
miTP	Minimum Transmission Point
MHz	Mega Hertz
MLL	Mode Lock Laser
MZM	Mach Zehnder Modulator
MWP	Microwave Photonics
MWPR	Microwave Photonics Radar
MTI	Moving Target Indication

N

NF	Noise Figure
NLFM	Non-Linear Frequency Modulated

O

O/E	Optical to Electrical
OSA	Optical Spectrum Analyser
OSB	Order Sideband

P

PCR	Pulse Compression Ratio
PD	Photodiode
PolM	Polarisation Modulator
PM	Power Meter
PS	Power Splitter
PSLR	Peak-to-Sidelobe Ratio

Q

Q-Point	Quadrature Point

R

RADAR	Radio Detection and Ranging
RR	Range Resolution

S

SA	Spectrum Analyser
SAR	Synthetic Aperture Radar
SBS	Stimulated Brillouin Scattering
SOI	Silicon-on-Insulator

T

TBWP	Time-Bandwidth Product

U

USB	Upper Sideband

V

VNA	Vector Network Analyser
VSG	Vector Signal Generator

W

WSS	Wavelength Selective Switch