High-Performance Microwave Photonic Signal Processing Using Brillouin Scattering

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by

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submitted in fulfillment of the requirements of the degree of

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Certificate

I hereby certify that the work which is being presented in the thesis entitled **"High-performance microwave photonic signal processing using Brillouin scattering"** in the fulfilment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY** and submitted to 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 2019 to March 2025 under the supervision of Prof. Amol Choudhary, Associate 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 ix.

Reena Parihar

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

Prof. Amol Choudhary
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Reena Parihar

Abstract

Microwave photonics (MWP) techniques offer significant potential in achieving exceptional performance characteristics, including lossless operation, power efficiency, high speeds, high extinction ratios, immunity to electromagnetic interference (EMI), high-frequency agility, fast reconfigurability, and high-resolution RF signal processing. The principles of integration, functionality, and performance form the foundation of MWP systems. Integration involves seamlessly combining electronic and photonic elements to create an MWP system. Functionality refers to the system's ability to surpass the limitations of traditional electronics. Performance encompasses the overall efficiency, speed, reliability, and responsiveness of the MWP system. Thus, the goal of this thesis is to develop a well-integrated, highly functional, and high-performance system. An analog photonic link (APL) plays a key role in converting electrical signals to optical and vice versa. Various parameters, such as input powers and bias angles of electro-optical modulation devices, are analyzed to optimize NF, G, SFDR, and CDR.

Stimulated Brillouin scattering (SBS) is particularly favored in microwave photonic signal processing due to its capability to deliver high-resolution filters with exceptional performance attributes such as ultra-high gain/loss, narrow linewidth, low threshold power, high extinction ratios, and tunability or programmability tailored to user requirements.

In many applications involving APLs, achieving low noise figure, minimizing nonlinear distortion, and maximizing link gain are critical objectives. Balancing these parameters poses a challenge, as enhancing one often compromises the others. SBS offers potential improvements for APLs by providing high resolution and increased gain. However, SBS may also introduce additional noise, necessitating thorough performance evaluation within APLs to optimize their overall performance. Therefore, our investigation focuses on exploring the potential integration of SBS in APLs to achieve high link gain while minimizing noise figure to practical limits and avoiding distortion.

सार

माइक्रोवेव फोटोनिक्स (एमडब्ल्यूपी) तकनीक असाधारण प्रदर्शन विशेषताओं को प्राप्त करने में महत्वपूर्ण क्षमता प्रदान करती है, जिसमें दोषरहित संचालन, बिजली दक्षता, उच्च गति, उच्च विलुप्ति अनुपात, विद्युत चुम्बकीय हस्तक्षेप (ईएमआई) से प्रतिरक्षा, उच्च आवृत्ति चपलता, तेजी से पुनर्संयोजन और उच्च-रिज़ॉल्यूशन RF सिग्नल प्रोसेसिंग शामिल हैं। एकीकरण, कार्यक्षमता और प्रदर्शन के सिद्धांत एमडब्ल्यूपी सिस्टम की नींव बनाते हैं। एकीकरण में एमडब्ल्यूपी सिस्टम बनाने के लिए इलेक्ट्रॉनिक और फोटोनिक तत्वों को सहजता से संयोजित करना शामिल है। कार्यक्षमता से तात्पर्य पारंपरिक इलेक्ट्रॉनिक्स की सीमाओं को पार करने की प्रणाली की क्षमता से है। प्रदर्शन में एमडब्ल्यूपी सिस्टम की समग्र दक्षता, गति, विश्वसनीयता और जवाबदेही शामिल है। इस प्रकार, इस थीसिस का लक्ष्य एक अच्छी तरह से एकीकृत, अत्यधिक कार्यात्मक और उच्च-प्रदर्शन प्रणाली विकसित करना है। एक एनालॉग फोटोनिक लिंक (एपीएल) विद्युत संकेतों को ऑप्टिकल में और इसके विपरीत परिवर्तित करने में महत्वपूर्ण भूमिका निभाता है। एनएफ, जी, एसएफडीआर, सीडीआर को अनुकूलित करने के लिए इलेक्ट्रो-ऑप्टिकल मॉड्यूलेशन उपकरणों की इनपुट पावर और बायस एंगल जैसे विभिन्न मापदंडों का विश्लेषण किया जाता है। उत्तेजित ब्रिलॉइन बिखराव (एसबीएस)को विशेष रूप से माइक्रोवेव फोटोनिक सिग्नल प्रोसेसिंग में पसंद किया जाता है, क्योंकि यह उच्च-रिज़ॉल्यूशन वाले फ़िल्टर देने की क्षमता रखता है, जिसमें असाधारण प्रदर्शन विशेषताएँ जैसे कि अल्ट्रा-हाई गेन/लॉस, संकीर्ण लाइनविड्थ, कम थ्रेशोल्ड पावर, उच्च विलुप्ति अनुपात और उपयोगकर्ता की आवश्यकताओं के अनुरूप ट्यूनेबिलिटी या प्रोग्रामेबिलिटी शामिल हैं। एपीएल से जुड़े कई अनुप्रयोगों में, कम शोर का आंकड़ा हासिल करना, नॉनलाइनियर विरूपण को कम करना और लिंक लाभ को अधिकतम करना महत्वपूर्ण उद्देश्य हैं। इन मापदंडों को संतुलित करना एक चुनौती है, क्योंकि एक को बढ़ाने से अक्सर दूसरे से समझौता होता है। एसबीएस उच्च रिज़ॉल्यूशन और बढ़ा हुआ लाभ प्रदान करके एपीएल के लिए संभावित सुधार प्रदान करता है। हालांकि, एसबीएस अतिरिक्त शोर भी ला सकता है, जिससे एपीएल के भीतर उनके समग्र प्रदर्शन को अनुकूलित करने के लिए गहन प्रदर्शन मूल्यांकन की आवश्यकता होती है। इसलिए, हमारी जांच शोर के आंकड़े को व्यावहारिक सीमाओं तक कम करने और विरूपण से बचने के साथ-साथ उच्च लिंक लाभ प्राप्त करने के लिए एपीएल में एसबीएस के संभावित एकीकरण की खोज पर केंद्रित है।

Table of Contents

List of Tables

List of Acronyms

A

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

B

BW	Bandwidth

C

CW	Continuous Waveforms
CDR	Compression Dynamic Range

D

dB	Decible
DDMZM	Dual Drive Mach Zehnder Modulator
DPMZM	Dual-Parallel-Mach-Zehnder-Modulator

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
FWHM	Full-Width Half Maximum

G

GHz	Giga Hertz
G	Link Gain

I

IM	Intensity Modulation
IMDD	Intensity Modulated Direct Detection

L

LD	Laser Diode
LFM	Linear Frequency Modulated
LSB	Lower Sideband

M

MHz	Mega Hertz
MZM	Mach Zehnder Modulator
MWP	Microwave Photonics

N

NF	Noise Figure
NL	Non-Linear
Norm	Normalized

O

O/E	Optical to Electrical
OSA	Optical Spectrum Analyser
OSSB	Optical single Sideband

P

PD	Photodiode
PM	Power Meter
PS	Power Splitter
PSLR	Peak-to-Sidelobe Ratio

Q

Q-Factor	Quality Factor

R

RADAR	Radio Detection and Ranging

S

SA	Spectrum Analyser
SFDR	Spurious-free Dynamic Range
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