

**LEVERAGING SILICON NANOPHOTONICS
FOR ON-CHIP AND OFF-CHIP
COMMUNICATION**

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**DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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FOR ON-CHIP AND OFF-CHIP
COMMUNICATION**

by

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Submitted

**in fulfilment of the requirements of the degree of Doctor of Philosophy
to the**



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Certificate

This is to certify that the thesis titled **LEVERAGING SILICON NANOPHOTONICS FOR ON-CHIP AND OFF-CHIP COMMUNICATION** being submitted by **Mr. Janibul Bashir** for the award of **Doctor of Philosophy** in Computer Science and Engineering is a record of bona fide work carried out by him under my guidance and supervision at the Department of Computer Science and Engineering, Indian Institute of Technology Delhi. The work presented in this thesis has not been submitted elsewhere, either in part or full, for the award of any other degree or diploma.

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Abstract

Numerous challenges present themselves when scaling traditional on-chip electrical networks to large many-core processors. Some of these challenges include high latency, limitations on bandwidth, and power consumption. Researchers have, therefore, been looking for alternatives. As a result, on-chip nanophotonics has emerged as a strong substitute for traditional electrical NoCs. However, optical networks are not a panacea to all our problems. They still have significant issues with respect to high static power consumption and scalability.

In this work, we propose various techniques to decrease the static power consumption in on-chip optical interconnects. We start by proposing two novel techniques to reduce static power consumption in photonic on-chip networks – a neural network based method for laser modulation by predicting optical traffic, and a distributed and altruistic algorithm for channel sharing – that are significantly closer to a theoretically ideal scheme. In spite of this, a lot of laser power still gets wasted. We propose to reuse this energy to heat micro-ring resonators (achieve thermal tuning) by efficiently recirculating it. These three methods help us significantly reduce the energy requirements.

However, area and manufacturing yield restrict such designs to single chips with small number of cores (16-32). As a result, we propose a scalable photonic based multi-chip architecture by leveraging the non-uniform cache architecture (NUCA) scheme on top of a virtual chip in order to decrease inter chip communication and increase the hit rate in the last level cache.

After that we proceed to improve the performance of GPUs with the help of silicon nanophotonics. We propose an energy efficient and scalable optical interconnect for GPUs. We intelligently divide the components in a GPU into different types of clusters and enable these clusters to communicate optically with each other. In order to reduce the network delay, we use separate networks for coherence and non-coherence traffic. Moreover, to reduce the static power consumption in optical interconnects, we modulate the off-chip light source by proposing a novel GPU specific prediction scheme for predicting on-chip network traffic.

Finally, we highlight the fact that unless security concerns are addressed, it will not be possible for third-party vendors to sell optical communication solutions at a large scale. As a result, we proposed a novel, secure, and efficient optical network that is immune to eavesdropping, spoofing, replay, and message-removal attacks. We leveraged some properties of optical networks to bring the expensive cryptographic operations out of the critical path in order to limit the overheads associated with our scheme.

सार

पारंपरिक ऑन-चिप विद्युत नेटवर्क को बड़े-कोर प्रोसेसर में स्केल करते समय कई चुनौतियां खुद को प्रस्तुत करती हैं। इनमें से कुछ चुनौतियों में उच्च विलंबता, बैंडविड्थ पर सीमाएं और बिजली की खपत शामिल हैं। इसलिए, शोधकर्ताओं ने विकल्प की तलाश की है। नतीजतन, ऑन-चिप नेनोफोटोनिक्स पारंपरिक विद्युत एनओसीएस के लिए एक मजबूत विकल्प के रूप में उभरा है। हालाँकि, ऑप्टिकल नेटवर्क हमारी सभी समस्याओं के लिए रामबाण नहीं हैं। उच्च स्थिर बिजली की खपत और मापनीयता के संबंध में उनके पास अभी भी महत्वपूर्ण मुद्दे हैं। इस काम में, हम ऑनचिप ऑप्टिकल इंटरकनेक्ट में स्थैतिक बिजली की खपत को कम करने के लिए विभिन्न तकनीकों का प्रस्ताव करते हैं। हम फोटोनिक ऑन-चिप नेटवर्क में स्थैतिक बिजली की खपत को कम करने के लिए दो उपन्यास तकनीकों का प्रस्ताव करके शुरू करते हैं - ऑप्टिकल ट्रेफिक की भविष्यवाणी करके लेजर मॉड्यूलेशन के लिए एक तंत्रिका नेटवर्क आधारित विधि, और चैनल साझा करने के लिए एक वितरित और परोपकारी एल्गोरिथ्म - जो सैद्धांतिक रूप से आदर्श के करीब हैं योजना। इसके बावजूद, लेजर की बहुत सी शक्ति अभी भी बर्बाद हो जाती है। हम माइक्रो-रिंग रेज़ोनेटर (थर्मल ट्यूनिंग को प्राप्त करने) को कुशलतापूर्वक पुनः प्रसारित करके इस ऊर्जा का पुनः उपयोग करने का प्रस्ताव करते हैं। ये तीन विधियां हमें ऊर्जा आवश्यकताओं को कम करने में मदद करती हैं। हालांकि, क्षेत्र और विनिर्माण उपज इस तरह के डिजाइनों को कम संख्या में कोर (सोलह-बत्तीस) के साथ एकल चिप्स तक सीमित करते हैं। परिणामस्वरूप, हम अंतर चिप संचार को कम करने और अंतिम स्तर कैश में हिट दर को बढ़ाने के लिए एक आभासी चिप के ऊपर गैर-समान कैश आर्किटेक्चर (एनयूसीए) योजना का लाभ उठाकर एक स्केलेबल फोटोनिक आधारित मल्टी-चिप वास्तुकला का प्रस्ताव करते हैं। उसके बाद हम सिलिकॉन नैनोकणों की मदद से जीपीयू के प्रदर्शन को बेहतर बनाने के लिए आगे बढ़ते हैं। हम जीपीयूएस के लिए एक ऊर्जा कुशल और स्केलेबल ऑप्टिकल इंटरकनेक्ट का प्रस्ताव देते हैं। हम समझदारी से घटकों को जीपीयू में विभिन्न प्रकार के समूहों में विभाजित करते हैं और इन समूहों को एक दूसरे के साथ वैकल्पिक रूप से संवाद करने में सक्षम बनाते हैं। नेटवर्क की देरी को कम करने के लिए, हम सुसंगतता और गैर-सुसंगत यातायात के लिए अलग-अलग नेटवर्क का उपयोग करते हैं। इसके अलावा, ऑप्टिकल इंटरकनेक्ट में स्थैतिक बिजली की खपत को कम करने के लिए, हम ऑन-चिप नेटवर्क ट्रेफिक की भविष्यवाणी के लिए एक उपन्यास जीपीयू विशिष्ट भविष्यवाणी योजना का प्रस्ताव करके ऑफ-चिप प्रकाश स्रोत को संशोधित करते हैं। अंत में, हम इस तथ्य को उजागर करते हैं कि जब तक सुरक्षा चिंताओं को संबोधित नहीं किया जाता है, तब तक तीसरे पक्ष के विक्रेताओं के लिए बड़े पैमाने पर ऑप्टिकल संचार समाधान

बेचना संभव नहीं होगा। नतीजतन, हमने एक उपन्यास, सुरक्षित और कुशल ऑप्टिकल नेटवर्क का प्रस्ताव रखा, जो ईव्सड्रॉपिंग, स्पूफिंग, रीप्ले और संदेश-हटाने के हमलों के लिए प्रतिरक्षा है। हमने अपनी योजना से जुड़े ओवरहेड्स को सीमित करने के लिए महंगे क्रिप्टोग्राफिक संचालन को महत्वपूर्ण पथ से बाहर लाने के लिए ऑप्टिकल नेटवर्क के कुछ गुणों का लाभ उठाया।

Contents

Certificate	i
Acknowledgements	iii
Abstract	v
1 Introduction	1
1.0.1 Advantages of optical on-chip networks	2
1.0.2 Current Scenario	3
1.0.3 Problems with existing Optical On-chip Networks	3
1.0.4 Thesis outline	4
2 A Survey of On-Chip Optical Interconnects	7
2.1 Introduction	7
2.1.1 Motivation for this Survey	9
2.1.2 Organization	9
2.2 Layers in an Optical NoC	10
2.2.1 Basic Background	10
2.2.2 Optical Devices used in Photonic Networks	11

2.2.3	Optical Architectures	12
2.2.4	Power Consumption	12
2.2.5	Applications	13
2.3	Optical Devices used in Photonic Networks	14
2.3.1	Light Sources: Laser	14
2.3.2	Signal Propagation: Waveguides	17
2.3.3	Modulation: Microring Resonators	21
2.3.4	Device Level Challenges	23
2.4	Architecture	27
2.4.1	Summary	27
2.4.2	Topology	27
2.4.3	Design and Operation	29
2.4.4	Crossbar Designs	30
2.4.5	Multi-stage Designs	33
2.4.6	Opto-Electric Designs	34
2.4.7	Protocols: Routing, Switching, and Flow Control	35
2.5	Power Reduction	39
2.5.1	Overview	39
2.5.2	Static Power Consumption	40
2.5.3	Dynamic Power Loss	43
2.6	Applications	44
2.6.1	Overview	44
2.6.2	Snoopy Cache Coherence	45

2.6.3	Barriers	45
2.6.4	LLC Access Protocol	45
2.6.5	Virtual Chip or Macrochip	46
2.7	Chapter conclusion	46
3	Predict, Share, and Recycle your Way to Low Power Nanophotonic Networks	49
3.1	Introduction	49
3.2	Background	52
3.2.1	Light Source	52
3.2.2	Tunable Power Splitters	52
3.2.3	Transmitter	53
3.2.4	Receiver	53
3.2.5	Optical Crossbar Based Topologies	53
3.2.6	Artificial Neural Networks	53
3.2.7	Photonic Heaters	54
3.3	Motivation	56
3.3.1	High Laser Power Consumption → Predict	56
3.3.2	Unbalanced Traffic → Share	57
3.3.3	Energy Wasted → Recycle	58
3.4	Design and Implementation	59
3.4.1	Overview	59
3.4.2	Prediction Mechanism	59
3.4.3	Arbitration Mechanism for Sharing Power	62
3.4.4	Recycling Power	66

3.4.5	Laser Controller	69
3.5	Evaluation	71
3.5.1	Experimental Setup	71
3.5.2	Power Models	76
3.5.3	Optical Vs Electrical Networks	79
3.5.4	Activity Prediction and Power Consumption	80
3.5.5	Comparison with ML Based Predictor	82
3.5.6	Performance Analysis	84
3.5.7	Power breakdown	87
3.5.8	Comparison between the Arbitration Schemes	88
3.5.9	Effect of Different Epoch Sizes	88
3.5.10	Scalability Analysis	89
3.5.11	Reuse of Wasted Power	91
3.6	Related Work	93
3.6.1	Prediction	93
3.6.2	Sharing	94
3.7	Chapter conclusion	95
4	GPUOPT: Power Efficient Photonic Network-on-Chip for a Scalable GPU	97
4.1	Introduction	97
4.1.1	Challenges	98
4.1.2	Our Solution	98
4.1.3	Summary of Results	99
4.1.4	Contributions	99

4.1.5	Organization of the Chapter	100
4.2	GPU organization and design	101
4.2.1	Architecture	101
4.2.2	Execution Model of a GPU	102
4.3	Benchmark Characteristics and Motivation	103
4.3.1	Baseline Architecture	103
4.3.2	GPU Workloads	103
4.3.3	Characterization	104
4.3.4	Summary	108
4.4	GPUOPT Topology	109
4.4.1	Overview	109
4.4.2	Design	109
4.4.3	Optical Crossbar	111
4.4.4	Optically Connected Memory (OCM)	114
4.5	Laser Power Management: <i>PS_GPUOPT</i>	115
4.5.1	Overview	115
4.5.2	Prediction Mechanism	115
4.6	Experimental Methodology	119
4.7	Experimental Results	121
4.7.1	Electrical Vs Optical	121
4.7.2	Analysis	121
4.7.3	Comparison with Prior Work on PNoCs	122
4.7.4	Analysis of the Prediction Scheme	126

4.8	Related Work	128
4.9	Chapter conclusion	129
5	NUPLet: A Photonics Based Multi-Chip NUCA Architecture	131
5.1	Introduction	131
5.2	Background and Related Work	133
5.2.1	Basics of Silicon Photonics	133
5.2.2	Related Work	134
5.3	Motivation	135
5.3.1	Unbalanced Inter-Chiplet Traffic → MWMR Design	135
5.3.2	Low Hit Rate in Remote Banks → Use NUCA	136
5.3.3	Expensive Inter-Chiplet Messages → Predict	137
5.4	Architecture of <i>NUPLet</i>	137
5.4.1	Basic Setup	137
5.4.2	On-Chip and Off-Chip Networks	138
5.4.3	NUCA Schemes	139
5.4.4	NUPLet	140
5.5	Evaluation	143
5.5.1	Experimental Setup	144
5.5.2	Hit Rate Comparison and Non-Home Bank Accesses	144
5.5.3	Prediction Accuracy	146
5.5.4	Contention at ICOSs	146
5.5.5	Performance Comparison	146
5.5.6	Laser Power Consumption	147

5.5.7	ED^2 Comparison	148
5.6	Chapter conclusion	148
6	SecONet: A Security Framework for a Photonic Network-on-Chip	151
6.1	Introduction	151
6.2	Background and Related Work	153
6.2.1	Basic On-chip Optical Communication Framework	153
6.2.2	Optical Waveguides	154
6.3	Motivation and Threat Model	154
6.3.1	Domain of Trust	154
6.3.2	Attacks on an SWMR Network	155
6.3.3	Attacks on an MWSR Network	156
6.4	Design and Implementation	156
6.4.1	Overview	156
6.4.2	Key Distribution Phase	157
6.4.3	Execution Phase	159
6.4.4	Verification Phase	161
6.5	Evaluation	162
6.5.1	Setup	162
6.5.2	Parameter Selection	162
6.5.3	Area and Delay Overheads	163
6.5.4	Effect of SecONet on Mean Packet Latency, Performance and Power Consumption	163
6.5.5	Analysis	164

6.6	Related Work on PNoC Security	165
6.7	Chapter conclusion	166
7	Conclusion and Future Work	167
7.1	Conclusion	167
7.2	Future Work	168
	Bibliography	171
	List of Publications	197
	Biography	199

List of Figures

1.1	Thesis outline	5
2.1	Evolution of optical communication [1]	8
2.2	A basic optical communication system	10
2.3	Layers in an optical NoC	11
2.4	Different types of waveguides	17
2.5	Taper	17
2.6	RSoft simulation (FDTD) of a 90° optical waveguide bend. Parameters: outer radius = $3.1\mu m$, inner radius = $2.9\mu m$, and width = $0.2\mu m$	19
2.7	Directional coupler. Simulation parameters: simulation type = BeamProp, width = $1\mu m$, separation = $0.2\mu m$, length of each waveguide = $50\mu m$	19
2.8	Y junction. Simulation parameters: simulation type = BeamProp, Angle of Y = 0.8 radians, width = $1\mu m$	19
2.9	MMI. Simulation parameters: simulation type = BeamProp, spacing = $6.2\mu m$, $W = 48\mu m$, $L = 680\mu m$, and $W_g = 3\mu m$	21
2.10	Schematic diagram of microring resonator	21
2.11	Microring resonator. Simulation parameters: simulation type = FDTD, gap = $0.05\mu m$, outer radius of ring = $1.8\mu m$, inner radius of ring = $1.6\mu m$, width = $0.2\mu m$, and height = $0.7\mu m$	21
2.12	Photo-detector circuit	23

2.13 Taxonomy of different architectures	27
2.14 Regular topologies	27
2.15 Routers	30
2.16 Flexishare	33
2.17 Sources of power loss in optical networks	40
3.1 Artificial neural network	54
3.2 Relative laser power consumption across different optical topologies (* Splash2 workloads)	56
3.3 Traffic injected across stations	57
3.4 Layout of the chip	59
3.5 Layout of a serpentine shaped topology with data, power, and reservation waveguides	63
3.6 PShaRe Arbitration flow-chart	65
3.7 Power distribution for reusing unused optical power	67
3.8 Achieved bandwidth	79
3.9 Optical vs electrical network (performance comparison)	80
3.10 Laser power comparison	81
3.11 Relative laser power consumption	83
3.12 Relative speedup	83
3.13 ED^2 comparison	84
3.14 Relative wait time at a station queue	84
3.15 Performance comparison	86
3.16 ED^2 comparison	86

3.17	Network power consumption breakdown	87
3.18	Relative laser power consumed by different arbitration schemes	88
3.19	Performance comparison using different epoch sizes	89
3.20	Comparison of performance: 128 cores	90
3.21	Comparison of performance: 256 cores	90
3.22	(Left) Floorplan for HotSpot. (Right) One Tile in a floorplan	91
4.1	(a) High level architectural diagram of a representative GPU (b) Organization of an SM containing 32 SPs, 16 LSUs and 8 SFUs. Adapted from [2]	102
4.2	2D layout of tiles	103
4.3	Relative performance comparison across different number of SMs	104
4.4	Memory access breakup	105
4.5	Breakup of the communication between the L1 and L2 caches	106
4.6	GPU performance sensitivity to NoC bandwidth ($X=0.5\text{TB/s}$)	107
4.7	Laser power consumption of the design in [3] as compared to an ideal system .	107
4.8	Topology of an optical NoC for GPU	110
4.9	Cross-sectional view of the chip	110
4.10	Power distribution sub-network	113
4.11	Flow of operations	114
4.12	Electrical vs optical networks	121
4.13	Performance comparison	123
4.14	Relative laser power consumption	124
4.15	Energy-Delay-Square product comparison	125
4.16	Relative speedup	126

4.17	Relative laser power consumption	127
5.1	Chiplet load distribution (* Splash benchmarks)	136
5.2	Comparison of number of accesses and hit rate in the LLC	136
5.3	NUPLet Architecture	138
5.4	LLC access flowchart	141
5.5	NUPLet Performance comparison	146
5.6	NUPLet Relative laser power comparison	147
5.7	NUPLet ED^2 comparison	148
6.1	Photonic on-chip communication framework	153
6.2	Attacks on the PNoCs (photonic NoCs)	155
6.3	Overview of the system	157
6.4	The key distribution protocol	158
6.5	Complete design of SecONet	161
6.6	Effect of hash and OTP units on the overall system performance	163
6.7	Effect of SecONet on packet latency	164
6.8	Effect of SecONet on the performance	164
6.9	Effect of SecONet on laser power consumption	165

List of Tables

1.1	Number of cores per multicore chip (not considering GPUs here)	2
3.1	PShaRe Treatise	51
3.2	Inputs to the ANN predictor	60
3.3	Final set of parameters	61
3.4	Operations for message transmission in PShaRe	66
3.5	Prediction and reconfiguration	70
3.6	Simulation parameters (also see [4])	73
3.7	Optical parameters [5, 6, 7, 8, 9, 10, 11, 12, 13, 14]	74
3.8	Area overheads of different structures	75
3.9	Overall area distribution	75
3.10	Analysis of prediction accuracy and contention at the stations	81
3.11	Thermal simulations and unused power	92
4.1	Description of Rodinia Benchmarks	104
4.2	Insights obtained in this section	108
4.3	Algorithm for laser power scaling	118
4.4	Architectural parameters	119

4.5	Optical parameters [15, 13, 16, 11, 17]	119
4.6	Optical resources	120
4.7	Analysis of the wait time and the number of tokens ($A = GPUOPT$, $B = PS_GPUOPT$)	122
5.1	Simulation parameters (also see [4])	143
5.2	Analysis of LLC hit rates and prediction accuracies (* Splash benchmarks) . .	145
6.1	Area and delay overheads (duly scaled to 14nm [18])	162