



KTH Electrical Engineering

MEMS tunable polarization rotator for optical communication

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1 Chapter 1

Introduction

Communication and collected thinking is the key to the development and continuous evolution of human civilization which is driven by data - “The new oil of this digital era”. With the advent of Internet of Things (IoT), it has been estimated that by 2020 there will be 26 billion connected devices [1] and all that can be connected will be connected. Today only about 40 percent [2] of the world’s population use the Internet and the amount of data produced per minute through different social media platform like Facebook, Youtube, Twitter, Flickr, Instagram, Linkedin, Blogger, Whatsapp etc. is already growing exponentially.

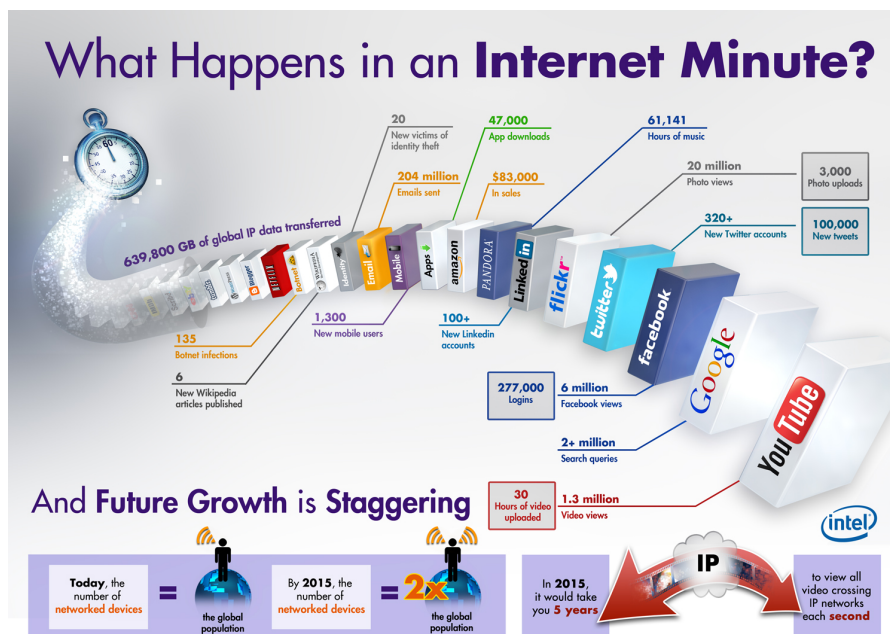
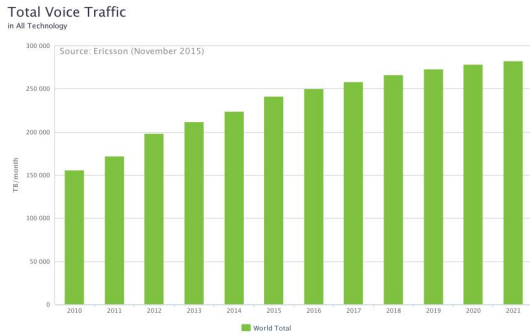


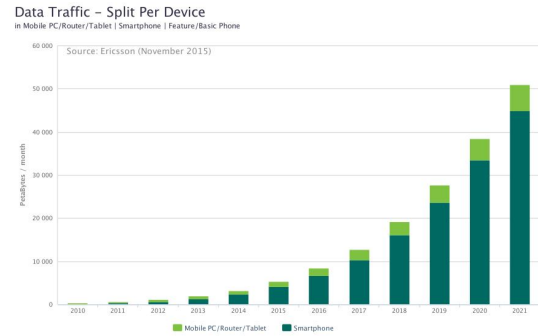
Figure 1.1: What happens on internet per minute [3]

Eventually, with the inclusion of world’s population into the cyberspace world this data growth will be more than ever.

Also, with the advent of mobile communications, there has been a huge surge in the voice as well as data traffic all over the world. It has been estimated in Ericsson’s mobility



(a) Voice data traffic forecast all over the world



(b) Data traffic forecast for different devices

Figure 1.2: Voice and data traffic growth by 2020, as per Ericsson generated using [5]

report [4] that 70 percent of world’s population will use smart-phones by 2020 and 90 percent of the world’s population over 6 years old will have a mobile phone by 2020.

Currently, the telecommunications industry is moving towards IP Multimedia Sub-system (IMS) core networks which is a transition towards full IP based networks. So how is this humongous traffic managed? The answer is the optical fiber, which serves as the backbone of all the communication systems. The performance of optical fiber network is unprecedented and it is this backbone which gives us an unfathomable user experience. The current internet architecture has already pushed the optical fiber to the network edges and the trend is to push it as closer to the processor as possible. This has already opened up a new area of “Siliconizing photonics” based on the decades of research obtained from microelectronics industry. The electronics industry have pushed the boundaries of the processing speed of Integrated circuit(s) (IC) after the invention of semiconductors and are currently at the edge where Moore’s Law is at its upper limit. Although, with the current technology we have a decent processing power but what about the interconnects between the IC. Transmission of signals through copper interconnects would definitely slow things down. Think of a data center processing peta-bytes of data per minute, where interconnects between processors can add up to a significant delay. These losses can be overcome by adding optical interconnects using the current technology which can also operate at low power and better efficiency catering to the needs of the environment.

1.1 Motivation

The movement of data in a computer is almost the equivalent of movement of traffic in a city, where data flows fast in the congested microprocessor but is delayed in the interconnects. Intel processor speed and bus speed comparison [6] shows that although we have achieved good processing speed, the interconnects always find difficulty in catching up with the processing speed. Obviously, the closer engineers can bring the optical superhighway to the microprocessor, the fewer copper bottlenecks can occur.

Until recently, exponential increases in the speed, efficiency, and processing power of conventional electronic devices were achieved largely through the downscaling and clustering of components on a chip. However, this trend toward miniaturization has yielded unwanted effects in the form of significant increases in noise, power consumption, signal propagation delay and aggravates already to serious thermal management problems. Alternatively, the wires can be made fatter, but then you'll run out of space and the packing density will be inefficient. As a result, traditional microelectronics will soon fall short of meeting market needs, inhibited by the thermal and bandwidth bottlenecks inherent in copper wiring. Photons don't suffer from these limitations; their biggest problems are absorption and attenuation, neither of which is an issue over the distances inside a computer, or even across a room. Today Silicon Photonics [7] Technology is a new approach to make optical devices out of silicon and use light (photons) to move huge amounts of data at very high speeds with extremely low power over a thin optical fiber rather than using electrical signals over a copper wire. Since, already enough capital investments has been done on perfecting the current fabrication technology and infrastructure, engineers are working on creating monolithic design of integrated circuits which use light in place of electric signals. Organizations are trying to bridge this gap by creating highly integrated photonic and electronic components that combine the functionality of conventional Complementary metal-oxide semiconductor (CMOS) circuits with the significantly enhanced system performance of photonic solutions. By allowing for the seamless integration of optical and electronic components on silicon-based substrates, this technology holds the key to fulfilling market needs for higher bandwidth and processing speed at lower power and cost.

Silicon Photonics is an emerging market and researchers are actively working on creating monolithic IC design with optical components to cope up with the future demands [8]. Researchers are coming up with new avenues indicating that fiber information capacity can be notably increased over previous estimates [9] which can double fiber optic capacity. The silicon photonics market is estimated to grow to 700 million USD by 2024 [10] with a Cumulative average growth rate (CAGR) of 38 percent. Photonic devices made on Silicon on Insulator (SOI) platform is compatible with CMOS electrical circuits since they are based on same material. It is also promising in developing on-chip integration for telecommunications applications and servers in data centers [11]. Various kinds of silicon photonic devices like switches [12, 13, 14], modulators [15, 16], photodetectors [17, 18], delay lines [19, 20], sensors [21, 22, 23] etc. have been reported till date. All these things have corroborated interest into silicon photonics which are based on SOI platform.

However, these photonic devices based on SOI waveguides are sensitive to polarization due to large structural birefringence, which might induce Polarization dependent loss (PDL), Polarization mode dispersion (PMD), and Polarization dependent wavelength characteristics (PD λ) limiting their usability. To overcome these challenges Polarization rotator (PR) are engineered on SOI for Optoelectronic integrated circuit (OEIC) and various designs have already been demonstrated [24, 25, 26, 27, 28, 29, 30] which will be discussed in later sections. The main principle of these proposed solutions are based on varying Refractive index (RI) by introducing asymmetry in the waveguide structure which

is not tunable. Also, in some cases the designs [31], if used in commercial applications for miniature interconnects, would incur inefficient packing density since too much space is required to achieve high and robust tuning. Also, Tunable polarization rotator (TPR) have been reported which works on the principle of Berry's phase, a quantum-mechanical phenomenon of purely topological origin [32]. But, since the design is based on out of place waveguides it might be difficult to efficiently achieve mass production without a complex manufacturing process. The general goal of the thesis work to realize efficient TPR using Microelectromechanical systems (MEMS) to achieve improvement over the current available research solutions, to cater needs of the future industry.

1.2 Objectives

The current situation landscape in Silicon Photonics is quite exciting and a number of problems are there in the industry to realize a final optimal and robust prototype. The main objective of this thesis work is to design and fabricate low power TPR which can primarily mitigate the drawbacks discussed earlier. To tune at sufficient low power, MEMS. The waveguides will be built upon current Silicon fabrication technology which will be characterized using an automated measurement setup to minimize coupling loss using grating couplers. In this thesis following objectives will be addressed:

- ☐ How to design a MEMS tunable polarization rotator?
- ☐ How to simulate the design using MEMS techniques like Comsol, CST etc.?
- ☐ How to effectively characterize the system with the measurements available?
- ☐ By how much can the power consumption be reduced in comparison to current state of the art?
- ☐ What is the polarization extinction range/ratio (PER) that can be achieved through redesign?
- ☐ What packing density can be achieved through this design in comparison to the available solution for OEIC?
- ☐ How easily can the design be fabricated?
- ☐ Efficiency of the fabricated device?

1.3 MEMS and silicon photonics

MEMS are micrometre-sized sensors and actuators that are used in many devices in our everyday life (eg. Gyrometer and accelerometer in our smartphones). Using the same fabrication technology, one can fabricate on-chip optical circuits, which drastically improve the performance of telecommunication systems. However, both MEMS and

silicon waveguides have been independently developed. This project aims to bring together both fields to try out new ideas to enable new applications and to improve existing ones.

1.4 Importance of these systems

Silicon photonics is on the verge of creating a newer technology trend. It is on the brink of creating a technological revolution where semiconductor industry stood back 60 years from now just before the discovery of transistors. If this technology is developed successfully it can keep up with the tremendous data processing power needed by the current networking servers to deliver services. Since use of optics can also increase the bandwidth in a many-fold manner it can cater the needs of data rate needed by the futuristic networks. Also, as the vision is to move everything closer to the chip this technology can deliver IC which can be easily fit into futuristic devices. Using MEMS for the tuning will ensure high resolution at very lower power. This is also important because light transmitted to an optical circuit will typically come from an optical fibre, and optical fibres emit light with random polarization. These systems can expand the boundary of optical networks and bring it closer to the end devices by transgressing the network edges where optical fibers are currently located.

1.5 Outline of this thesis

The outline of the thesis is as follows: Background, motivation and the research questions being addressed, is discussed in Chapter 1. In Chapter 2, the current state of art for the available solution is discussed along with the background literature required. Here, also the working principle of the current available design are explained along with the areas which can be improved. Chapter 3 discusses about the design of the final system and the results obtained about the simulation setup. In Chapter 4, documentation about the fabricated design is provided along with currently available standard fabrication technologies. Results and characterization are an important part of the work, which is discussed in Chapter 5. Finally, Chapter 6 and 7 discusses about the conclusion and future work possibilities respectively along with the known limitations of the system if any.

2

Chapter 2

State of the art

The most interesting aspect of fabricating optical waveguides from silicon is based on low primary cost of material, the mature and evolved manufacturing techniques owing to decades of research and the potential to develop monolithic IC using the same substrate.

2.1 Theoretical background of SOI waveguide

Although silicon is the optimal material for electronics, only recently silicon is being considered as a practical option for OEIC solutions. Silicon has many properties conducive to fiber optics. The band gap of silicon (~ 1.1 eV) is such that the material is transparent to wavelengths commonly used for optical transport ($\sim 1.3\text{ }\mu\text{m}$ - $1.6\text{ }\mu\text{m}$). One can use standard CMOS processing techniques to sculpt optical waveguides onto the silicon surface. Similar to an optical fiber, these optical waveguides can be used to confine and direct light as it passes through the silicon [33]. Due to the wavelengths typically used for optical transport and silicon's high index of refraction, the feature sizes needed for processing these silicon waveguides are on the order of $0.5\text{ }\mu\text{m}$ - $1\text{ }\mu\text{m}$. The lithography requirements needed to process waveguides with these sizes exist today. If we push forward to leading-edge research currently under way in the area of Photonic band-gap (PBG) devices, today's state-of-the-art 90 nm fabrication facilities should meet the technical requirements needed for processing PBG devices. What this says is that we may already have all or most of the processing technologies needed to produce silicon-based photonic devices for the next decade. In addition, the same carriers used for the basic functionality of the transistor (i.e. electrons and holes) can be used to modulate the phase of light passing through silicon waveguides and thus produce 'active' rather than passive photonic devices. Finally, if all this remains CMOS-compatible, it could be possible to process transistors alongside photonic devices, the combination of which could bring new levels of performance, functionality, power and size reduction, all at a lower cost.

2.1.1 Maxwell's equations

To understand the.....

- 2.1.2 Eigenvector and eigenvalue**
- 2.1.3 Optical polarization and modes**
 - 2.1.3.1 TE mode**
 - 2.1.3.2 TM mode**
- 2.1.4 Optical waveguides**
 - 2.1.4.1 Planar waveguides**
 - 2.1.4.2 Rib waveguides**
 - 2.1.4.3 Polarization in optical waveguides**
- 2.1.5 Jones vector**
- 2.1.6 Transfer matrix (S-matrix)**
- 2.1.7 Poincaré sphere**
- 2.2 Theoretical background of MEMS**
 - 2.2.1 Overview**
 - 2.2.2 Actuation principle**
- 2.3 Polarization rotator**
 - 2.3.1 Passive polarization rotator**
 - 2.3.2 Active polarization rotator**

3

Chapter 3

Design and simulation

3.1 Approach

3.2 Designing the experiment

3.2.1 Design principle

3.2.2 Use case: Active polarization rotator

3.3 Choice of simulation

3.4 Simulation results and analysis

4

Chapter 4

Fabrication

5

Chapter 5

Results

5.1 Experimental setup for measurement

5.2 Results

5.3 Analysis

6

Chapter 6

Conclusions

7

Chapter 7

Limitations and future work

7.1 Limitations

7.2 Future work

Abbreviations

- CAGR** Cumulative average growth rate. 3
- CMOS** Complementary metal-oxide semiconductor. 3, 6
- IC** Integrated circuit(s). 2, 3, 5
- IMS** IP Multimedia Subsystem. 2
- IoT** Internet of Things. 1
- MEMS** Microelectromechanical systems. ii, 4, 5, 7
- OEIC** Optoelectronic integrated circuit. 3, 4, 6
- PD λ** Polarization dependent wavelength characteristics. 3
- PDL** Polarization dependent loss. 3
- PER** polarization extinction range/ratio. 4
- PMD** Polarization mode dispersion. 3
- PR** Polarization rotator. 3
- RI** Refractive index. 3
- SOI** Silicon on Insulator. ii, 3, 6
- TPR** Tunable polarization rotator. 4

Bibliography

- [1] “Gartner says the internet of things installed base will grow to 26 billion units by 2020.” <http://www.gartner.com/newsroom/id/2636073>, 2013. [Online; accessed 26-Jan-2016].
- [2] “Number of Internet Users (2015) - Internet Live Stats.” <http://www.internetlivestats.com/internet-users/>, 2015. [Online; accessed 22-Jan-2016].
- [3] “What Happens in an Internet Minute [Infographic] | Daily Infographic.” <http://www.dailyinfographic.com/what-happens-in-an-internet-minute-infographic>, 2013. [Online; accessed 29-Jan-2016].
- [4] “Ericsson Mobility Report: 70 percent of world’s population using smartphones by 2020.” <http://www.ericsson.com/news/1925907>, 2015. [Online; accessed 06-Feb-2016].
- [5] “Ericsson traffic exploration infographic.” <http://www.ericsson.com/TET/trafficView/loadBasicEditor.ericsson>, 2015. [Online; accessed 06-Feb-2016].
- [6] “ARK | Your Source for Intel® Product Specifications.” <http://ark.intel.com/>, 2015. [Online; accessed 06-Feb-2016].
- [7] “Silicon photonics.” https://en.wikipedia.org/wiki/Silicon_photonics/, 2015. [Online; accessed 06-Feb-2016].
- [8] N. Savage, “Linking Chips With Light.” <http://spectrum.ieee.org/semiconductors/optoelectronics/linking-chips-with-light>, 2015. [Online; accessed 06-Feb-2016].
- [9] E. Temprana, E. Myslivets, B. P.-P. Kuo, L. Liu, V. Ataie, N. Alic, and S. Radic, “Overcoming Kerr-induced capacity limit in optical fiber transmission,” *Science*, vol. 348, pp. 1445–1448, June 2015.
- [10] “Silicon photonics market to grow at CAGR of 38% from \$25m in 2013 to \$700m in 2024.” http://www.semiconductor-today.com/news_items/2014/JUL/YOLE_180714.shtml, 2014. [Online; accessed 06-Feb-2016].
- [11] B. Jalali and S. Fathpour, “Silicon Photonics,” *Journal of Lightwave Technology*, vol. 24, pp. 4600–4615, Dec. 2006.
- [12] M. C. Wu, T. J. Seok, S. Han, and N. Quack, “MEMS-Enabled Scalable Silicon Photonic Switches,” p. FW3B.2, OSA, 2015.

- [13] D. Nikolova, S. Rumley, D. Calhoun, Q. Li, R. Hendry, P. Samadi, and K. Bergman, "Scaling silicon photonic switch fabrics for data center interconnection networks," *Optics Express*, vol. 23, p. 1159, Jan. 2015.
- [14] L. Lu, L. Zhou, X. Li, and J. Chen, "Low-power 2x2 silicon electro-optic switches based on double-ring assisted Mach–Zehnder interferometers," *Optics Letters*, vol. 39, p. 1633, Mar. 2014.
- [15] P. Dong, C. Xie, L. L. Buhl, Y.-K. Chen, J. H. Sinsky, and G. Raybon, "Silicon In-Phase/Quadrature Modulator With On-Chip Optical Equalizer," *Journal of Lightwave Technology*, vol. 33, pp. 1191–1196, Mar. 2015.
- [16] C. Chen, C. He, D. Zhu, R. Guo, F. Zhang, and S. Pan, "Generation of a flat optical frequency comb based on a cascaded polarization modulator and phase modulator," *Optics Letters*, vol. 38, p. 3137, Aug. 2013.
- [17] Y. Urino, Y. Noguchi, M. Noguchi, M. Imai, M. Yamagishi, S. Saitou, N. Hirayama, M. Takahashi, H. Takahashi, E. Saito, T. Shimizu, M. Okano, N. Hatori, M. Ishizaka, T. Yamamoto, T. Baba, T. Akagawa, S. Akiyama, T. Usuki, D. Okamoto, M. Miura, J. Fujikata, D. Shimura, H. Okayama, H. Yaegashi, T. Tsuchizawa, K. Yamada, M. Mori, T. Horikawa, T. Nakamura, and Y. Arakawa, "Demonstration of 12.5-Gbps Optical Interconnects Integrated with Lasers, Optical Splitters, Optical Modulators and Photodetectors on a Single Silicon Substrate," p. Tu.4.E.1, OSA, 2012.
- [18] C.-M. Chang, J. H. Sinsky, P. Dong, G. de Valicourt, and Y.-K. Chen, "High-power dual-fed traveling wave photodetector circuits in silicon photonics," *Optics Express*, vol. 23, p. 22857, Aug. 2015.
- [19] S. Garcia and I. Gasulla, "Design of heterogeneous multicore fibers as sampled true-time delay lines," *Optics Letters*, vol. 40, p. 621, Feb. 2015.
- [20] M. Mattarei, A. Canciamilla, S. Grillanda, and F. Morichetti, "Variable Symbol-Rate DPSK Receiver Based on Silicon Photonics Coupled-Resonator Delay Line," *Journal of Lightwave Technology*, vol. 32, pp. 3317–3323, Oct. 2014.
- [21] S. Janz, A. Densmore, D.-x. Xu, P. Waldron, J. Lapointe, G. Lopinski, T. Mischki, P. Cheben, A. Delâge, B. Lamontagne, and J. H. Schmid, "Silicon Waveguide Photonics for Biosensing Applications," p. IWA1, OSA, 2007.
- [22] G. Lim, U. P. DeSilva, N. R. Quick, and A. Kar, "Laser optical gas sensor by photoexcitation effect on refractive index," *Applied Optics*, vol. 49, p. 1563, Mar. 2010.
- [23] E. Ryckeboer, R. Bockstaele, M. Vanslembrouck, and R. Baets, "Glucose sensing by waveguide-based absorption spectroscopy on a silicon chip," *Biomedical Optics Express*, vol. 5, p. 1636, May 2014.

- [24] A. Xie, L. Zhou, J. Chen, and X. Li, “Efficient silicon polarization rotator based on mode-hybridization in a double-stair waveguide,” *Optics Express*, vol. 23, p. 3960, Feb. 2015.
- [25] A. V. Velasco, M. L. Calvo, P. Cheben, A. Ortega-Moñux, J. H. Schmid, C. A. Ramos, i. M. Fernandez, J. Lapointe, M. Vachon, S. Janz, and D.-X. Xu, “Ultracompact polarization converter with a dual subwavelength trench built in a silicon-on-insulator waveguide,” *Optics Letters*, vol. 37, p. 365, Feb. 2012.
- [26] D. Leung, B. Rahman, and K. Grattan, “Numerical Analysis of Asymmetric Silicon Nanowire Waveguide as Compact Polarization Rotator,” *IEEE Photonics Journal*, vol. 3, pp. 381–389, June 2011.
- [27] J. Wang, B. Niu, Z. Sheng, A. Wu, X. Wang, S. Zou, M. Qi, and F. Gan, “Design of a SiO₂ top-cladding and compact polarization splitter-rotator based on a rib directional coupler,” *Optics Express*, vol. 22, p. 4137, Feb. 2014.
- [28] D. Dai and J. E. Bowers, “Novel concept for ultracompact polarization splitter-rotator based on silicon nanowires,” *Optics Express*, vol. 19, p. 10940, May 2011.
- [29] J. C. Wirth, J. Wang, B. Niu, Y. Xuan, L. Fan, L. Varghese, D. E. Leaird, and A. Weiner, “Efficient Silicon-on-Insulator Polarization Rotator based on Mode Evolution,” p. JW4A.83, OSA, 2012.
- [30] L. Chen, C. R. Doerr, and Y.-K. Chen, “Compact polarization rotator on silicon for polarization-diversified circuits,” *Optics Letters*, vol. 36, p. 469, Feb. 2011.
- [31] J. D. Sarmiento-Merenguel, R. Halir, X. Le Roux, C. Alonso-Ramos, L. Vivien, P. Cheben, E. Durán-Valdeiglesias, I. Molina-Fernández, D. Marris-Morini, D.-X. Xu, J. H. Schmid, S. Janz, and A. Ortega-Moñux, “Demonstration of integrated polarization control with a 40 dB range in extinction ratio,” *Optica*, vol. 2, p. 1019, Dec. 2015.
- [32] Q. Xu, L. Chen, M. G. Wood, P. Sun, and R. M. Reano, “Electrically tunable optical polarization rotation on a silicon chip using Berry’s phase,” *Nature Communications*, vol. 5, p. 5337, Nov. 2014.
- [33] G. Reed and A. Knights, *Silicon Photonics: An Introduction*. Wiley, 2004.