

Taking silicon photonics modulators to a higher performance level: state-of-the-art and a review of new technologies

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Abstract. Optical links are moving to higher and higher transmission speeds while shrinking to shorter and shorter ranges where optical links are envisaged even at the chip scale. The scaling in data speed and span of the optical links demands modulators to be concurrently performant and cost-effective. Silicon photonics (SiPh), a photonic integrated circuit technology that leverages the fabrication sophistication of complementary metal-oxide-semiconductor technology, is well-positioned to deliver the performance, price, and manufacturing volume for the high-speed modulators of future optical communication links. SiPh has relied on the plasma dispersion effect, either in injection, depletion, or accumulation mode, to demonstrate efficient high-speed modulators. The high-speed plasma dispersion silicon modulators have been commercially deployed and have demonstrated excellent performance. Recent years have seen a paradigm shift where the integration of various electro-refractive and electro-absorptive materials has opened up additional routes toward performant SiPh modulators. These modulators are in the early years of their development. They promise to extend the performance beyond the limits set by the physical properties of silicon. The focus of our study is to provide a comprehensive review of contemporary (i.e., plasma dispersion modulators) and new modulator implementations that involve the integration of novel materials with SiPh.

Keywords: high-speed modulators; silicon photonics; plasma dispersion effect; ferroelectrics; graphene; III–V on Si; organic (electro-optic) materials.

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1 Introduction

High-speed transceivers for short-reach (few cm to few tens of km) and long-haul optical communication links require high-performance modulators in their transmitter optical subassembly.^{1–3} The key performance parameters for an efficient modulator are (a) high modulation efficiency^{4–7} in amplitude or phase by a drive signal that is compliant with the complementary metal-oxide-semiconductor (CMOS) circuitry^{8,9} [for phase modulators, the modulation efficiency is defined as the product

of voltage V_π applied to the phase shifter to achieve π phase shift and the length L of the phase shifter—a smaller $V_\pi \cdot L$ represents higher modulation efficiency; for amplitude modulation, the ratio of extinction ratio (ER) to an applied voltage for a given length of the modulator represents the modulation efficiency and large values are desired]; (b) low insertion loss (IL),^{10–12} both low loss in the active and passive parts of the modulator; (c) tens of gigabits per second (Gb/s)^{13–17} modulation speed to support the future capacity demands of the optical communication networks; (d) energy consumption to be as low as a few tens of fJ/bit;^{18–20} (e) large ER—typically ~ 4 dB for ~ 2 km transmission links and ~ 8 dB for tens of km long transmission links—to ensure high optical signal-to-noise ratio for maintaining a low

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Silicon Photonics The State Of The Art

Laurent Vivien, Lorenzo Pavesi



Silicon Photonics The State Of The Art:

Silicon Photonics Graham T. Reed, 2008-05-23 Silicon photonics is currently a very active and progressive area of research as silicon optical circuits have emerged as the replacement technology for copper based circuits in communication and broadband networks The demand for ever improving communications and computing performance continues and this in turn means that photonic circuits are finding ever increasing application areas This text provides an important and timely overview of the hot topics in the field covering the various aspects of the technology that form the research area of silicon photonics With contributions from some of the world's leading researchers in silicon photonics this book collates the latest advances in the technology *Silicon Photonics the State of the Art* opens with a highly informative foreword and continues to feature the integrated photonic circuit silicon photonic waveguides photonic bandgap waveguides mechanisms for optical modulation in silicon silicon based light sources optical detection technologies for silicon photonics passive silicon photonic devices photonic and electronic integration approaches applications in communications and sensors *Silicon Photonics the State of the Art* covers the essential elements of the entire field that is silicon photonics and is therefore an invaluable text for photonics engineers and professionals working in the fields of optical networks optical communications and semiconductor electronics It is also an informative reference for graduate students studying for PhD in fibre optics integrated optics optical networking microelectronics or telecommunications **Silicon Photonics** Graham T. Reed, 2008

Handbook of Silicon Photonics Laurent Vivien, Lorenzo Pavesi, 2013-04-26 The development of integrated silicon photonic circuits has recently been driven by the Internet and the push for high bandwidth as well as the need to reduce power dissipation induced by high data rate signal transmission To reach these goals efficient passive and active silicon photonic devices including waveguide modulators photodetectors multiplexers light sources and various subsystems have been developed that take advantage of state of the art silicon technology Suitable for both specialists and newcomers *Handbook of Silicon Photonics* presents a coherent and comprehensive overview of this field from the fundamentals to integrated systems and applications It covers a broad spectrum of materials and applications emphasizing passive and active photonic devices fabrication integration and the convergence with CMOS technology The book's self contained chapters are written by international experts from academia and various photonics related industries The handbook starts with the basics of silicon as an optical material It then describes the building blocks needed to drive integrated silicon photonic circuits and explains how these building blocks are incorporated in complex photonic electronic circuits The book also presents applications of silicon photonics in numerous fields including biophotonics and photovoltaics With many illustrations including some in color this handbook provides an up to date reference to the broad and rapidly changing area of silicon photonics It shows how basic science and innovative technological applications are pushing the field forward *Silicon Photonics Design* Lukas Chrostowski, Michael Hochberg, 2015-03-12 From design and simulation through to testing and fabrication this hands on

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Programmable Integrated Photonics José Capmany, Daniel Pérez, 2020 This is the first comprehensive self contained introduction to the emergent field of Programmable Integrated Photonics It covers theoretical and practical aspects ranging from basic technologies and the building of photonic component blocks to design alternatives and principles of complex programmable photonic circuits and their applications

Principles of Photonic Integrated Circuits Richard Osgood jr., Xiang Meng, 2021-05-21 This graduate level textbook presents the principles design methods simulation and materials of photonic circuits It provides state of the art examples of silicon indium phosphide and other materials frequently used in these circuits and includes a thorough discussion of all major types of devices In addition the book discusses the integrated photonic circuits chips that are currently increasingly employed on the international technology market in connection with short range and long range data communication Featuring references from the latest research in the field as well as chapter end summaries and problem sets Principles of Photonic Integrated Circuits is ideal for any graduate level course on integrated photonics or optical technology and communication

Integrated Photonics for

Data Communication Applications Madeleine Glick, Ling Liao, Katharine Schmidtke, 2023-07-26 Integrated Photonics for Data Communications Applications reviews the key concepts design principles performance metrics and manufacturing processes from advanced photonic devices to integrated photonic circuits The book presents an overview of the trends and commercial needs of data communication in data centers and high performance computing with contributions from end users presenting key performance indicators In addition the fundamental building blocks are reviewed along with the devices lasers modulators photodetectors and passive devices that are the individual elements that make up the photonic circuits These chapters include an overview of device structure and design principles and their impact on performance Following sections focus on putting these devices together to design and fabricate application specific photonic integrated circuits to meet performance requirements along with key areas and challenges critical to the commercial manufacturing of photonic integrated circuits and the supply chains being developed to support innovation and market integration are discussed This series is led by Dr Lionel Kimerling Executive at AIM Photonics Academy and Thomas Lord Professor of Materials Science and Engineering at MIT and Dr Sajan Saini Education Director at AIM Photonics Academy at MIT Each edited volume features thought leaders from academia and industry in the four application area fronts data communications high speed wireless smart sensing and imaging and addresses the latest advances Includes contributions from leading experts and end users across academia and industry working on the most exciting research directions of integrated photonics for data communications applications Provides an overview of data communication specific integrated photonics starting from fundamental building block devices to photonic integrated circuits to manufacturing tools and processes Presents key performance metrics design principles performance impact of manufacturing variations and operating conditions as well as pivotal performance benchmarks

Silicon Photonics Lorenzo Pavesi, 2004-03-04 This book gives a fascinating picture of the state of the art in silicon photonics and a perspective on what can be expected in the near future It is composed of a selected number of reviews authored by world leaders in the field and is written from both academic and industrial viewpoints An in depth discussion of the route towards fully integrated silicon photonics is presented This book will be useful not only to physicists chemists materials scientists and engineers but also to graduate students who are interested in the fields of microphotonics and optoelectronics

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