1. Nonlinear response of Si Photonics resonators for reservoir computing neural network

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Abstract: *Nowadays, Information Photonics is extensively studied and sees applications in many fields. The interest in this breakthrough technology is mainly stimulated by the possibility of achieving real-time data processing for high-bandwidth applications, still implemented through small-footprint devices that would allow for breaking the limit imposed by Moore's law. One potential breakthrough implementation of information photonics is via integrated photonic circuits. Within this approach, the most suitable computational scheme is achieved by integrated photonic neural networks. In this chapter, we provide a review of one possible way to implement a neural network by using silicon photonics. Specifically, we review the work we performed at the Nanoscience Laboratory of the University of Trento. We present methodologies, results, and future challenges about a delayed complex perceptron for fast data processing, a microring resonator exploiting nonlinear dynamics for a reservoir computing approach, and a microring resonator with the addition of a feedback delay loop for time series processing.*

1.1 Introduction

The interest in Artificial Neural Networks (ANNs) has considerably increased in recent years due to their versatility, which allows for dealing with a huge class of problems [1]. Nowadays, ANNs are mostly implemented on electronic circuits, in particular, on Von Neumann architectures in their different specifications such as the general purposes CPU (Central Processing Units), the massively parallel GPU (Graphical Processing Units) or the specialized integrated circuits used to accelerate specific task such as the TPU (Tensor Processing Units) [2, 3, 4]. Very-large-scale ANN models have been elaborated which outperform human minds in given tasks [5, 6] at the expense of large training times and huge power consumption [7, 8, 9]. Other intrinsic limits of electronic ANNs are related, for example, to the ease in interference between electrical signals, the difficulty in handling a large number of floating point operations and a low parallel computing efficiency [10, 11, 12]. A possible solution to these limitations is provided by Photonic Neural Networks (PNNs) which enable high-speed, parallel transmission (Wavelength Division Multiplexing, WDM) and low power dissipation [11, 10]. PNNs have the same overall architecture as an ANN, namely, they are made by several interconnected neurons where each neuron receives multiple inputs and feeds multiple other neurons (Fig. 1.1). The received inputs are weighted, combined, and processed by each neuron which through a nonlinear activation function feeds its interconnected neurons. When optics comes into

2. Photonics of metasurfaces

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Abstract: *Recently, metasurfaces have gained a lot of attention in the field of nanophotonics because of their capabilities to act as optical systems with performance that exceeds those of conventional diffractive optics. Here, we review some of these recent achievements, with particular attention to dielectric structures for shaping optical wavefronts. We present the mechanisms for obtaining phase control and controlling the angular response. Then, we report applications in linear and nonlinear optics. We conclude with an outlook on future perspectives and challenges that still need to be tackled.*

2.1 Introduction

Over the past few years, metamaterials [1, 2] have have attracted great interest due to their remarkable electromagnetic properties. Metamaterials are arrays of well-designed scattering elements which exhibit peculiar electromagnetic responses such as zero-index materials [3], negative-index media [4, 5], and ultra-high index materials [6, 7]. The high diffusion of these platforms has been favored by advances in the nanofabrication of large-area arrays of metallic and dielectric nano-resonators with high precision, reasonable throughput and relative ease of production. Among all the possible realizations of metamaterials, metasurfaces are among the most prevalent. Metasurfaces are made of periodic (or aperiodic) repetition of individual scatterers where the thickness and periodicity are in general smaller or similar to the impinging wavelength. The final response of the surface is determined by the geometrical shape of the resonators and their spatial distribution. The sub-wavelength scatterer that form the metasurface are often referred as 'meta-atoms'.

Recently, the flexibility offered by metasurfaces is recognized as an important strategy for molding electromagnetic propagation, including polarization conversion [8, 9], wavefront shaping [10, 11], radiation control [12, 13] and energy concentration [14, 15]. Nowadays metasurfaces attract enormous attention from the research communities. Due to the strong wavefront molding capability offered by metasurfaces at the nanoscale level, many meta-devices have been demonstrated either from the theoretically and experimentally viewpoint, such as invisible cloak [16, 17], absorber [18, 19, 20], vortex beam generator [21], with a particular focus on meta-lens [22, 23, 24, 25] and holography [26, 27, 28]. All

3. Materials and configurations for efficient nonlinear conversion in photonic circuits

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Abstract: *Nonlinear phenomena in integrated structures have been widely studied in the last forty years for their unprecedented capability to manipulate the properties of optical signals. Optical fiber has proved a powerful medium for the exploitation of nonlinear effects, however, the footprint of fiber devices is very large, thus preventing their massive exploitation in compact systems. The advent of integrated photonic circuits has made possible the implementation of nonlinear operations on small-scale integrated devices by adopting materials which exhibit nonlinearity coefficients orders of magnitude higher than that of silica glass. The combination of such material properties with the capabilities offered by the CMOS fabrication routines has opened the path to the investigation of several integrated platforms, where the nonlinear phenomena are boosted by extreme mode confinement and precise engineering of the dispersion properties of the interacting fields. A huge amount of exciting research has been developed over the years, and some outcomes are reviewed in this chapter with a specific emphasis on the research activity carried out in Italian research centres and universities.*

3.1 Introduction

Over the last few decades, nonlinear optics has enabled the development of a large variety of applications with considerable impact on daily life and society. Most of these applications as environmental monitoring, high-resolution spectroscopy, advanced devices for medical diagnosis, manufacturing and materials processing, scientific instrumentation and high-capacity telecommunications are well-established commercial successes [1]. In addition, for other emerging applications such as, for example, quantum science, neuromorphic computing or coherent lidars, nonlinear optics is likely to become a key enabling technology in the next few years [2, 3, 4]. Similarly to the evolution experienced by datacomms, a shift towards integration technologies in nonlinear optics would substantially accelerate the development of novel applications and also enlarge existing markets through the reduction of the cost and size of the devices. Integrated platforms are natural candidates for nonlinear operations owing to the strong light confinement combined with high material nonlinearity and low loss, thus promising the advent of low-power nonlinear integrated photonic devices [5, 6, 7]. Nowadays the development of a robust and standardized nonlinear integrated platform is still an open issue. Indeed nonlinear photonic circuits require advanced processing maturity of the materials and fabrication routines relying on CMOS fabrication facilities and, at the same time, the demand for low-power nonlinear applications asks for low propagation losses, high nonlinear figure of merit and

4. Graphene photonics for optical and wireless communications

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Abstract: *Graphene is a gapless material exhibiting extraordinary electrical, optical and mechanical properties. For this reason, an extensive study of graphene applications has been carried out in the last decade. In this chapter we walk through the graphene optical properties used to implement integrated photonic devices and circuits. We will analyze how the introduction of graphene as active material in integrated photonic circuits can improve the next generation telecom and datacom systems. Specifically we will detail the design of ultrafast modulators and detectors developed at CNIT, allowing to implement integrated photonics platforms entirely based on graphene as active material. Moreover, we will show the use of graphene detectors for the realization of optically-based sub-THz wireless links for the next generation 6G technology.*

4.1 Introduction

Photonics, i.e. the use of light to transmit and process information, is the key ingredient that will lead to the technological revolution generated by the widespread use of artificial intelligence. The fourth generation, 4G, of communications has allowed a great development of the voice and data service and has simplified the transition to the remote use of machines. The main feature of 5G instead is the presence of various types of communication with very different requirements: very wide bandwidth, ultra-reliable and very low latency (the time interval between when the signal is sent to the system and the moment in which answers)[1]. This is essential, given that some applications require real-time controls, commands and responses (URLLC, ultra reliable and low latency communication)[2]. Traditional communications are increasingly supported by those between objects (Internet of Things (IoT)). We need an increase in performance, a reduction in costs and energy consumption, and a decrease in the price of products. The first 5G networks already offer download speeds of over 500 megabits per second (in 4G the national average is 28 megabits per second). The power consumption is lower than 4G. The applications cover various areas: from communication services with machines in industries, to augmented and virtual reality, telemedicine, drones, brain-computer interfaces, home automation sensors, and many others[3].

Another aspect that will make digital services more interactive will be the integration of the communication network with artificial intelligence (AI). AI will act as "sixth sense“ at the service of society, superimposing information processed in real time on our perceptions[4]. This is a new challenge. Artificial Intelligence based services are progressing very fast, most of the applications in several fields will adopt this new technology

5. Modeling and mitigation of nonlinear effects in optical fiber systems

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Abstract: *This chapter provides a description of the most recent modeling activity in optical communications carried out in the Italian academia, which culminated in what is known as the Gaussian Noise (GN) model and its variants. The GN model has become nowadays the de-facto industry reference model for design and performance prediction of modern long-haul dispersion-uncompensated coherent optical systems and networks [1, 2]. Moreover, the chapter presents some recent results on fiber nonlinearity mitigation, focusing on digital backpropagation and constellation shaping strategies, and describes some bounding techniques that have been recently proposed to study the capacity limits of the nonlinear optical fiber channel.*

5.1 Introduction: Historical perspective

In the 1960's two major events sparkled the beginning of optical communications: 1) the invention of the laser and 2) the production of the first low-loss optical fibers [3]. The first optical communication links became commercial in the 1980's [4]. In their first 50 years, up to about 2010, optical communications used the On-Off keying binary modulation format with an incoherent receiver. The operation was called intensity-modulation with direct-detection (IM-DD). The carrier was a laser, light was transmitted during a “1” and no light during a “0” symbol. The detector was an energy (i.e., squared amplitude) detector, while the phase of the received laser field was disregarded since it was impractical to track it. In the 1990's wavelength division multiplexing (WDM), the optical version of frequency division multiplexing, was introduced by transmitting and amplifying many optical lasers in parallel on the same fiber link, thanks to the invention of an ultra-wide band optical amplifier known as the Erbium-doped fiber amplifier (EDFA) [5]. Very long-haul WDM terrestrial and submarine links were since then designed, but the prolonged interaction of WDM signals along the fiber line caused nonlinear interactions among them, mostly manifesting as four-wave mixing (FWM). It was soon discovered that the higher the fiber chromatic dispersion (to first order called group-velocity dispersion (GVD)), the smaller was the received FWM. However IM-DD systems could not tolerate the massive build-up of GVD since the DD receiver was intrinsically unable to equalize it (it was only about a decade after the revival of coherent communications that another Italian group

6. Space-division multiplexing in multi-core and multi-mode fibers

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Abstract: *Space is the only degree of freedom of the electromagnetic wave that is unused in conventional fiber-optic communication systems, which makes spatial multiplexing the only viable approach to scale the capacity of future fiber-optic systems in response to the ever growing demand for data traffic. A special implementation of space-division multiplexed (SDM) transmission, intensely researched worldwide over the past decade, is the one based on the use of multi-core and multi-mode fibers, where multiple spatial channels are integrated in a single fiber. This chapter reviews some of the work performed by the Italian optical communications community in this domain, in the framework of the CNIT National Laboratory of Advanced Optical Fibers for Photonics.*

6.1 Introduction

Space-division multiplexing (SDM) has been in the spotlight of research on fiber-optic communications since the beginning of the past decade, when it appeared that a capacity crisis of the global fiber-optic network was imminent [1]. Indeed, studies of the fiber-optic channel capacity [2] were reporting that the transmission throughput of hero experiments was only a factor of two below the theoretical limit dictated by Shannon's theorem, while at the same time the demand for data traffic in commercial systems was continuing its exponential growth [3]. In those years fiber-optic systems were taking full advantage of the fiber's conventional transmission band (the C-band) through wavelength-division multiplexing (WDM). Moreover, with the maturity of coherent-transmission technology, it became possible to make use of advanced modulation techniques enabled by digital signal

7. Hollow-core fibers for optical fiber communications

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Abstract: *This chapter presents an overview of the main characteristics of hollow-core fibers (HCFs) and discusses their applications in long-haul high-capacity optical transmission systems, highlighting the major challenges and opportunities.*

7.1 Introduction

Hollow-core optical fibers have been studied and developed for several decades. In principle, by guiding light in air rather than in a solid material, these fibers have many potential advantages with respect to silica-core fibers, among which low-nonlinearity and low-latency, as well as high bandwidth, low dispersion, high damage threshold and low backscattering. In particular, low-non linearity and wide bandwidth, if accompanied by the low losses recently demonstrated by nested-antiresonant nodeless fiber (NANF) design, are potentially extremely useful characteristics to increase the throughput of transmission systems.

This chapter first describes the charactersitics of hollow-core fibers in Section 2, highlighting the waveguiding mechanism and the main properties. A novel coupled-mode theory for hollow-core fibers is then introduced in Section 3, enabling an accurate modeling of both geometrical and anisotropy deformations in the fibers. Finally, Section 4 investigates the use of NANFs in long-haul high-capacity transmission systems, both showing record-achieving experimental results and discussing the potential performance of NANFs in future ultra-wideband optical systems.

7.2 Description and properties of hollow-core fibers

7.2.1 Introduction

The first studies of hollow core fibers (HCFs) date back to the 60's of the last century with the seminal work of Marcatili and Schmeltzer [1]. A hollow core fiber offers several advantages with respect to a solid core fiber: no (or ultra-low) absorption and Rayleigh scattering by the core material, no (or ultra-low) non-linearity, very low dispersion, diffractionless light-gas and liquid-gas interaction. In the Marcatili's conception hollow core fibers were composed by a simple hole surrounded by a homogeneous dielectric material. Their main drawback was the high so-called leakage or confinement loss

8. Prospects of optical wireless solutions for data center networks

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Abstract: *Data Center (DC)'s are steadily growing in size and complexity; correspondingly, the internal network and the amount of traffic that it transports are also exploding. Nowadays, the high-speed transmission inside the DC is achieved by optical fiber links, which come with huge amounts of cables. This brings issues in terms of installation and maintenance: the wired network becomes often involved and, as an example, adding new links is practically difficult. Most importantly, cables take space, which is becoming a practical issue, e.g., they reduce air flow and thus impact the cooling of the equipment. An effective alternative can be to realize high-capacity Optical Wireless Communication (OWC) links. Recently, very high-speed demonstrations of the technology have been presented and in line of principle we could obtain the same speed values of fiber communications. The use of these links can allow reducing the number of cables and is thus becoming attractive. In this paper, we present an evolution path towards the use of OWC in DC's. We first review the architectures that have been proposed, then we present system alternatives and finally analyze the device needs.*

8.1 Introduction

It is known that DC growth is continuing at steady pace: in the next few years, it was estimated that worldwide spending on DC equipment will be on the order of 200 billion of USD per year. As a relevant consequence, the intra-DC traffic is correspondingly rising. This comes with key issues about the architecture of the Data Center Network (DCN) and the physical solutions used to provide the intra-DC connectivity. Today, most of the intra-DC communications are at very high speed ($> 100\,\text{Gbit/s}$), thus rely on optical fibers; indeed, an impressive number of connections is present, which gives huge practical problems. Installation, maintenance, reconfigurability are all affected, as could be expected. Side effects are related to power consumption because large bundles of fiber cables in small spaces can reduce the air flow significantly: this can have a dramatic impact on the heat dissipation of the equipment, which is a well-known key problem. Therefore, power consumption and cooling can be affected by the number of wired connections [1].

Consequently, an increasing attention is devoted to alternative technologies for DCN's, both in terms of architecture and of hardware options. Among them, high-speed wireless communication, even over limited distances, looks a promising alternative that can allow

9. Overview on the Recent Evolution in High-Speed Optical Access Networks

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Abstract: *In this Chapter, we give an overview of the current status and expected medium-long term (5-10 years from now) evolution of optical fixed access networks, which have seen an enormous growth in deployment in Europe in the last decade, with an annual Compounded Average Growth Rate (CAGR) that is steadily above 10% in most EU Countries. Up to now (2022), this growth in commercial volumes was mostly led by the extensive deployment of Fiber-to-the-Home (FttH and its FttX variants). In the future, it is expected that optical access networks, while continuing their growth in FttH market penetration, will also become more and more the fundamental transport technology of 5G and next generation 6G mobile wireless networks, and in general of new network edge applications.*

9.1 Introduction

In the last decade, the structure of fixed access networks, i.e., the last part of national cabled networks reaching the end-users, has steadily evolved towards optical fiber solutions, so that today (2023) Fiber-to-the-Home (FttH) and all its FTTx variants are the typical deployed solutions for most households, at least in large European cities. This trend was driven by a mix of end-user requirements (that are consistently asking for higher bit rates per household) and also by specific EU policies that pushed each EU Country to accelerate in fiber deployment. All versions of the EU Digital Agenda Directives ratified after 2010 have constantly requested a growth in fiber access by “raising the bar” in the bit rate per user and coverage requests. In particular:

- the first EU Digital Agenda (released in 2015) set a target of 30 Mbps to all users and 100 Mbps to at least 50% of the users [1] to be reached by the year 2020;

10. Optical Access for 5G and B5G

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Abstract: *Disaggregated, virtualized, and open next-generation eNodeB (gNB) could bring several benefits to the 5G and beyond Next Generation Radio Access Network (NG-RAN) by enabling more market competition and customer choice, lower equipment costs, and improved network performance. This can be achieved through gNB Remote Unit (RU), Central Unit (CU) and Distributed unit (DU) separation, CU and DU function virtualization, and zero touch RAN management and control. However, to achieve the performance required by specific foreseen 5G usage scenarios (e.g., Ultra Reliable Low Latency Communications — URLLC), offloading selected disaggregated gNB functions into an accelerated hardware becomes a necessity. Another important challenge is supporting the RU-DU and CU-DU interfaces with large capacity, low-latency and energy-efficient transport networks when needed. Optical Access networks are among the proposed transport networks. In particular, passive optical networks through either a point-to-point connection (e.g., a dedicated wavelength in NG-PON2) or a share in time of their overall capacity are suitable candidates because of their low cost, large capacity and, in some deployments, low-latency. For what concerns energy efficiency, the utilisation of Time Division Duplexing (TDD) in 5G enables the implementation of schemes exploiting the opportunities provided by the TDD pattern. For example, Cooperative Dynamic Bandwidth Allocation (CO DBA) was proposed for reducing the fronthaul latency contribution in Time Division Multiplexing Passive Optical Networks (TDM-PON). The contribution of this chapter is twofold. One is to highlight the advantages and drawbacks of utilising some network function acceleration in 5G disaggregated network elements in terms of latency and energy efficiency. The other one is to show how the duplexing pattern utilised in 5G networks (i.e., TDD) can be exploited to reduce the energy consumption of a software-defined TDM-PON x-Haul.*

10.1 Introduction

The 5G RAN is evolving towards the Next Generation RAN (NG-RAN) where disaggregated Next Generation Evolved NodeBs (gNBs) are utilized. Each gNB consists of a Central Unit (CU) that is connected to one or more Distributed Units (DU) through the midhaul interface, and each DU is connected to one or more Radio Units (RU) that implement Radio Frequency (RF) functions using the fronthaul interface [1].

11. Novel architectures for metro and transport optical networks

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Abstract: *Network upgrades are continuously required to support traffic growth while limiting costs and network complexity. In this chapter we overview several novel technical directions for an effective network upgrade arising in metro and transport optical networks. Multi-band transmission may be an efficient solution to postpone expensive installations of new fibers. Novel network architectures such as filterless networks may reduce the complexity of optical nodes by relying on passive splitters and couplers that replace costly Wavelength Selective Switches (WSS). Then, a proper network automation needs to be enabled for efficient connection provisioning and maintenance. In particular, network disaggregation has been introduced at several levels with the objective of removing the "vendor lock-in", thus enabling more open networks and reducing costs for network operators. Network automation also relies on descriptions of the network architecture including physical layer constraints and network functionalities possibly exploiting data sensed from the system. Recently, the concept of "digital twin" has been introduced and extended for optical networks with the aim of representing physical layer and network components. This chapter will first introduce upgrades to multi-band systems and recent architectures for filterless optical networks. Then, it introduces the concept of digital twin for optical networks. Finally, disaggregated Software Defined Networking (SDN) control including telemetry functionalities will be presented.*

11.1 Network architecture and upgrades

11.1.1 Multi-band optical networking

Multi-band optical networking is being investigated as a possible solution to increase network infrastructure life. Indeed, currently, optical fibers are mainly used in the C-band and recently in C+L. Taking advantage of the unused portions of the spectrum (e.g., S- and E-band) may be an efficient solution to accommodate an increase in traffic without installing new fibers [1]. Research is thus investigating multi-band transmission and networking to evaluate and enable such network upgrades. Some issues need to be

12. Machine Learning for future optical network automation

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Abstract: *Machine Learning (ML) tools have recently been adopted for a wide range of automated operations in optical networking, moving fundamental steps towards the paradigm of zero-touch management of optical-network infrastructures. Such network systems are capable not only of self-monitoring, but also of self-reconfiguration and self-repair, thanks to advanced capabilities such as autonomous learning, root-cause analysis and optimized decision-making. This chapter provides an overview of the application of ML-based methods for a variety of autonomous transmission and network-related tasks, including optical amplifiers tuning, lightpath QoT estimation, fault management, resource allocation in metro/core topologies and in inter/intra-datacenter optical networks.*

12.1 Introduction

Nowadays, the amount and variety of information retrievable from optical networks is extremely large (e.g., traffic samples, network alarms, signal quality indicators, etc.). Due to the high volumes, time-variable dynamics and heterogeneity of such information, Machine Learning (ML) tools are being increasingly investigated as key instruments to automate optical network planning and operation, and are deemed among the most important enablers for zero-touch and softwarized networks, as demonstrated by the numerous studies recently appeared in this field [1]. This chapter focuses on the applications of ML tools to future-proof optical networks, overviewing the most recent trends in this domain.

The discussion is organized in two main parts, where different types of data, namely, signal quality metrics and network data, are leveraged to address various optical network use-cases. In particular, in Sec. 12.2, Quality of Transmission (QoT) estimation, optical network failure management and optical amplifiers control are discussed, while in Sec. 12.3 we overview the application of ML in resource assignment in optical core and data center networks.

12.2 Application of ML based on signal quality metrics

Before the establishment of an optical lightpath and during its operation, signal quality metrics such as Bit Error Rate (BER), Optical Signal-to-Noise Ratio (OSNR), Q-Factor,