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LASER & PHOTONICS REVIEWS

Editorial

Integrated optics – from single photon sources to complex photonic circuits

The fascinating concept of 'Integrated Optics', with the meaning of optical devices and circuits realised in a patterned planar waveguide format, was first described by Stewart Miller in a historic special issue of the Bell System Technical Journal (BSTJ), as long ago as 1969 [1]. His original paper "outlines a proposal for a miniature form of laser beam circuitry. Index of refraction changes of the order of 10^{-2} or 10^{-3} in a substrate such as glass allow guided laser beams of width near 10 microns. Photolithographic techniques may permit simultaneous construction of complex circuit patterns. ..." Miller envisaged an analogous development to Integrated Electronics with a continuously growing density of integration (Moore's law). However, it turned out, that the growth of integration density in the optical domain was much slower than in Electronics. There are several reasons that explain the different rates of development. An important one is that a single material – silicon - has an almost completely dominant role in Integrated Electronics, as the base material for more and more complex integrated circuits (IC). The situation in the domain of *Integrated Optics* is quite different. There is a wide range of materials used for specific applications. As an example, the integrated (Mach-Zehnder type) optical modulators in the ferroelectric material $LiNbO_3$ are among the key components that enable the worldwide optical internet. Interestingly, silicon also – in the form of silicon-on-insulator (SOI) – has emerged during the last few years as a strong contender for various applications of Integrated Optics. In addition, besides glasses of different composition, III-V-semiconductors nowadays play an essential role, not only for the fabrication of more and more complex laser structures, but also as base material for photonic integrated circuits combining lasers, filters, modulators, beam splitters, ... on a single chip. This approach seems to fulfil the vision of Stewart Miller in a nearly ideal way.

The objective of this special issue of Lasers and Photonics Reviews (LPR) is to get an idea of the state-of-the-art in Integrated Optics through reports of leading scientists and engineers about the latest developments. Our intention is that the broad range of materials, devices, circuits and applications of Integrated Optics is represented by selected examples. However, it has turned out that a single special issue was not sufficient - and, finally, we have ended up with two issues, both being greater than the average length of a standard issue of LPR.

In this first issue, our tour d'horizon starts with the paper "On the genesis and evolution of Integrated Quantum Optics" by Sébastien Tanzilli, Anthony Martin, Olivier Alibart, and Daniel B. Ostrowsky (Université de Nice - Sophia Antipolis, France). It introduces and reviews the emerging and fascinating field of Integrated Quantum Optics, which has applications in quantum communications and quantum information processing. It describes the development of integrated single-photon and photon-pair sources, up-conversion detectors, quantum memories and devices for linear optical quantum computing. Many of the devices are based on (periodically poled) waveguides in ferroelectric materials, such as lithium niobate. They may well serve as building blocks for more complex quantum systems in the near-future.

Due to the high refractive index contrast between waveguide core and its surrounding, SOI waveguides can have an extremely small cross-section with strong mode confinement allowing bending radii even below 5µm. This enables the development of very compact ring resonators and of further devices of unprecedented small size. Moreover, CMOS fabrication technology can be used, enabling integrated optical circuits of high integration density. The significance of silicon waveguide technology is emphasized by three articles. In "Silicon microring resonators" by Wim Bogaerts, Peter de Heyn, Thomas van Vaerenbergh, Katrien De Vos, Shankar Kumar Selvaraja, Tom Claes, Pieter Dumon, Peter Bienstman, Dries van Thourhout, and Roel Baets (Ghent University - Information Technology and IMEC, Belgium), an overview of silicon ring resonators is given. The basic theory is discussed - and applied to the peculiarities of submicron SOI waveguides. Modelling results are compared to quantitative measurements. Furthermore, some promising applications of silicon ring resonators are discussed: filters and optical delay lines, label-free biosensors, and active rings for efficient modulators and even light sources. The paper "Progress and technical challenge for planar waveguide devices" by Katsunari Okamoto (AiDi Corporation, Tsukuba, Japan), reviews progress and the future prospects of two kinds of planar waveguide devices: (a) silica and silicon photonics multi/demultiplexers for communications and signal-processing applications - and (b) a novel waveguide spectrometer based on Fourier transform spectroscopy for sensing applications. In the article "The first decade of coupled resonator optical waveguides (CROWs): bringing slow light to applications" by Francesco Morichetti, Carlo Ferrari, Antonio Canciamilla, and Andrea Melloni (Politecnico di Milano, Dipartimento di Elettronica e Informazione, Italy), the history of CROWs is discussed, from the original idea to recent applications. CROWs are fancy waveguides consisting of a chain of coupled ring resonators on a photonic chip. Light propagates through CROWs with a reduced speed and enhanced intensity, boosting light-matter interaction while keeping information undistorted. In the paper design criteria, fundamental limits, and sensitivity to fabrication tolerances are discussed to provide a realistic perspective on future applications.

Glass systems also are often used in Integrated Optics, e. g. for beam-splitters, arrayed waveguide gratings and rare-earth doped amplifiers, which are all applied in optical communications. The recent development of waveguides in chalcogenide glasses is of special interest due to their attractive ultra-fast non-linear properties. Benjamin J. Eggleton, Trung D. Vo, Ravi Pant, Jochen Schröder, Mark D. Pelusi, Duk-Yong Choi, Stephen J. Madden and Barry Luther-Davies (CUDOS, University of Sydney and Australian National University, Canberra, Australia) review, in the contribution “Photonic chip based ultrafast optical processing based on high nonlinearity dispersion engineered chalcogenide waveguides”, their recent progress in developing integrated nonlinear optical devices for ultrafast all-optical signal processing. An unprecedented processing bandwidth is achieved by using dispersion engineered chalcogenide waveguides. Recent experiments and demonstrations of photonic logic operations are described.

III-V semiconductor materials are invariably used in Integrated Optics in the form of multi-layer epitaxial waveguides – and, at least nominally, as single-crystal wafer sections. This statement certainly applies for the case of the materials involved in the research desribed in the articles by Yu and co-workers and by Smit and co-workers. At the wavelengths emitted by quantum cascade lasers, the electrode metallisation can contribute significantly to the waveguide confinement via plasmonic effects. In the article “Beam engineering of quantum cascade lasers” by Nanfang Yu, Qijie Wang, and Federico Capasso (Harvard University, Cambridge, USA, and Nanyang Technological University, Singapore), the recent progress on beam engineering of mid-infrared and terahertz quantum cascade lasers (QCLs) is reviewed. Two approaches are presented - using either designer plasmonic structures or deformed microcavities. With both concepts, remarkable results have been achieved in controlling the directionality and output power level of QCLs. Finally, Meint Smit, Jos van der Tol, and Martin Hill (COBRA – TU Eindhoven, The Netherlands) give an impressive overview of the ongoing increase of complexity of InP-based Photonic Integrated Circuits (ICs). In their article “Moore’s law in photonics”, the similarities and differences between photonic and microelectronic integration technology are discussed - and a vision of the development of photonic integration in the coming decade is given.

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