Photonic-Electronic Ultra-Broadband Signal Processing: Concepts, Devices, and Applications

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***Abstract* — Combining photonic integrated circuits (PIC) with millimeter-wave electronics opens novel perspectives in generation and detection of ultra-broadband signals with disruptive potential for a wide variety of applications. Here, we will give an overview on our recent progress in the field of ultra-broadband photonic-electronic signal processing, covering device concepts such as silicon plasmonic integration, signal processing concepts such as Kramers-Kronig-based phase reconstruction of THz signals, as well as application demonstrations in the field of high-speed wireless data transmission.**

Keywords — photonic integration, silicon photonics, plasmonics, hybrid integration, THz communications, Kramers-Kronig receiver

I. INTRODUCTION

Photonic integrated circuits (PIC) and co-integration of such circuits with high-speed electronics has seen great progress in recent years, mainly driven by the need for high-speed optoelectronic transceivers in telecommunication and data-center networks. However, when complemented by ultra-fast signal converters such as electro-optic modulators or photodetectors, the technology base of integrated photonics can also be leveraged for generation and detection of ultra-broadband signals with bandwidths of hundreds of gigahertz. In this paper, we give an overview on our recent work in the field of photonic-electronic signal processing, covering device technologies for ultra-broadband signal conversion as well as the associated signal processing concepts and application demonstrations in the field of high-speed wireless communications.

II. DEVICE TECHNOLOGIES: HYBRID PHOTONIC CIRCUITS, SILICON PLASMONICS, AND CHIP-SCALE FREQUENCY COMB SOURCES

Large-scale on-chip integration of optical devices has seen tremendous progress over previous years, and several platforms have reached industrial maturity. However, these circuits mainly rely on monolithic integration concepts, where all devices are realized on the same material system. This approach enables highest scalability, but the performance of the resulting systems is often limited by the underlying integration platform. A prominent example is the silicon photonic integration platform: From a technological point of view, silicon represents an excellent material system, enabling large-scale fabrication by mature CMOS processes [1] along with monolithic co-integration of photonic and electronic circuits [2]. From a functional point of view, however, silicon falls short of distinct properties that are indispensable when it comes to high-performance photonic-electronic signal processing. Specifically, the silicon photonics platform lacks efficient light sources as well as ultra-fast photodetectors or electro-optic modulators that can operate at bandwidths of hundreds of gigahertz.

These shortcomings can be overcome by combining silicon photonic circuits with other material systems that offer the desired functionality. In a first approach, we have explored hybrid integration on the package level, exploiting direct-write two-photon lithography to fabricate three-dimensional (3D) free-form single-mode waveguides, so-called photonic wire bonds [3], or facet-attached beam-shaping elements such as micro-lenses that allow for highly efficient coupling at relaxed alignment tolerances [4]. We have demonstrated the viability of the concept by realizing functional optical assemblies that rely on 3D-printed coupling elements and that can be used for optical communications [5] or for high-speed photonic-electronic signal processing [6].

This approach is complemented by hybrid on-chip integration of silicon photonic circuits together with plasmonic structures and/or with advanced electro-optic materials. Combining silicon photonic waveguides with plasmonic structures allows for ultra-broadband optical-to-electrical

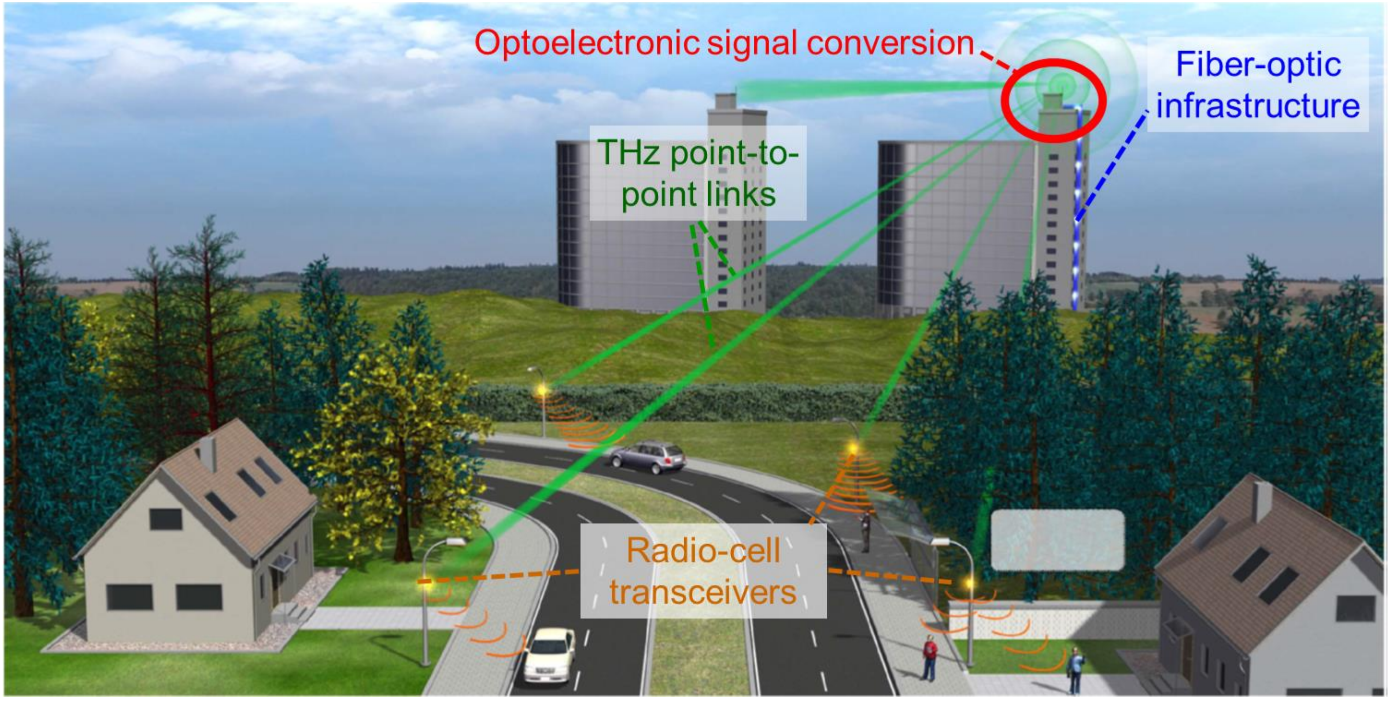

Figure 1: Artist's view of a future wireless network, consisting of a multitude of small radio cells (brown) that are connected by THz point-to-point links (green). Direct optoelectronic signal conversion between THz waves and optical signals by means of, e.g., III-V-based uni-travelling carrier (UTC) photodiodes [24] or photoconductors [6], silicon plasmonic plasmonic internal photoemission devices (PIPED) [8], or ultra-fast plasmonic-organic hybrid (POH) electro-optic modulators [16] allows to seamlessly interface these THz links to fiber-optic communication infrastructures (blue). (Figure adapted from [6])

conversion in so-called plasmonic internal photoemission devices (PIPED) [7], [8], whereas silicon-organic hybrid (SOH) integration [9], [10] offers an attractive route towards low-loss electro-optic (EO) modulators that can be operated at high data rates [11], [12] and low voltage levels [13], [14], [15]. Plasmonic-organic hybrid (POH) integration finally combines silicon-plasmonic circuits with advanced organic materials, thereby boosting the bandwidth of EO modulators to hundreds of gigahertz [16]. This opens an attractive route towards conversion of ultra-broadband electrical signals onto optical carriers.

When it comes to synthesis and analysis of arbitrary ultra-broadband waveforms, optical frequency combs can act as highly precise sources of well-defined optical carriers that may be used for spectrally sliced detection of optical signals [17], [18]. In this context, chip-scale frequency comb generators are of particular interest, combining compact footprint with high robustness and comb-line spacings of tens of gigahertz. Over the recent years, we have explored the viability of such devices in the field of massively parallel optical communications [19], where so-called dissipative Kerr-soliton (DKS) frequency combs [20] and quantum-dash mode-locked lasers [21], [22], [23] have proven particularly useful. In the future, these devices may be exploited for ultra-broadband photonic-electronic analogue-to-digital converters (ADC) that rely on spectrally sliced detection of signals using optical frequency combs as highly precise multi-wavelength local oscillators (LO) [17].

III. SIGNAL PROCESSING CONCEPTS AND APPLICATIONS: ULTRA-BROADBAND WIRELESS COMMUNICATIONS AND ANALOGUE-TO-DIGITAL CONVERSION

The photonic-electronic technology base opens new routes towards advanced signal processing concepts and novel application fields. Frequency down-conversion by photomixing in ultra-broadband III-V-based uni-travelling carrier (UTC) photodiodes [24] or plasmonic internal photoemission devices (PIPED) [6] opens is an attractive approach to generation of broadband electric signals at carrier frequencies of hundreds of gigahertz. When it comes to detection of sub-THz band-pass signals, down-conversion to the baseband can be accomplished by optical local-oscillator signals in combination with high-speed PIPED [8] or with photoconductors based on low-temperature-grown InGaAs/InAlAs heterostructures [6], [25]. Alternatively, ultra-broadband electro-optic modulators that exploit, e.g., the POH approach, can be used for first transferring electrical signals to an optical carrier [16], where they can then be processed further, e.g., by spectrally sliced detection in ultra-broadband photonic-electronic ADC [17]. Conversion of THz data signals to optical carriers lends itself to realizing seamless interfaces between sub-THz point-to-point links and fiber optic infrastructures in future wireless access networks [16], see Figure 1.

Besides exploiting optical device technologies, broadband signal processing can also benefit from theoretical concepts that are inspired by photonics. An example of such a concept is the detection of quadrature-amplitude-modulation (QAM) signals with simple envelope detectors and the reconstruction of the signal phase by means of so-called Kramers-Kronig processing [26], which was originally developed for reception of optical QAM signals via a single photodiode. We have generalized this approach and applied it to the detection of QAM data signals at sub-THz carrier frequencies via ultra-broadband Schottky-barrier diodes [27]. In our experiments, we demonstrated wireless transmission of a net date rate of 110 Gbit/s at a carrier frequency of 0.3 THz over a distance of more than 100 m [27]. The THz receiver stands out due to its technical simplicity, which may be key to making terahertz communications a viable option for future high-capacity wireless infrastructures.

ACKNOWLEDGMENTS

This work was supported by the European Research Council (ERC consolidator grant 'TeraSHAPE', no. 773248), by the Deutsche Forschungsgemeinschaft (DFG) via the projects PACE (#403188360) and GOSPEL (# 403187440), which are part of the Priority Programme "Electronic-Photonic Integrated Systems for Ultrafast Signal Processing" (SPP 2111), via the Excellence Cluster 3D Matter Made to Order (EXC-2082/1 – 390761711), and via the DFG project HIPES (#383043731), by the Bundesministerium für Bildung und Forschung (BMBF) Project PRIMA (# 13N14630) and SPIDER (# 01DR18014A), by the project TeraSlice (# 863322) and PIXAPP (# 731954) under European Union's Horizon 2020 Research and Innovation Programme, by the Alfried Krupp von Bohlen und Halbach Foundation, by the Gips-Schüle Foundation, by the Helmholtz International Research School of Teratronics (HIRST), and by the Karlsruhe School of Optics and Photonics (KSOP). The work relies on instrumentation funded by the European Regional Development Fund (ERDF, grant EFRE/FEIH_776267), the Deutsche Forschungsgemeinschaft (DFG; grants DFG/INST 121384/166-1 and DFG/ INST 121384/167-1) and the Hector Stiftung (Hector Foundation).

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