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Silicon-organic hybrid (SOH) devices and their use in comb-based communication systems

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***Abstract* — Advanced wavelength-division multiplexing (WDM) requires both efficient multi-wavelength light sources to generate optical carriers and highly scalable photonic-electronic interfaces to encode data on these carriers. In this paper, we give an overview on our recent progress regarding silicon-organic hybrid (SOH) integration and comb-based WDM transmission.**

Keywords — Silicon photonics, silicon-organic hybrid (SOH) integration, frequency combs, optical interconnects

SUMMARY

High-speed optical interconnects within and between data centers rely on advanced wavelength-division multiplexing (WDM) schemes that are scalable to large channel counts. This requires power-efficient photonic-electronic interfaces that can be densely integrated at low cost as well as chip-scale light sources that can provide a multitude of narrowband optical carriers for WDM transmission. Photonic-electronic interfaces can be efficiently realized on the silicon photonic platform, in particular when exploiting the unique performance of organic electro-optic materials using the silicon-organic hybrid (SOH) approach. At the same time, optical frequency combs lend themselves as multi-wavelength sources for scalable WDM transmission. This paper gives an overview on our recent progress in the fields of SOH integration and comb-based WDM transmission and discusses the prospects of merging the two approaches.

Silicon photonics shows tremendous potential for large-scale photonic-electronic integration by fabless fabrication of photonic and electronic circuits [1]. Silicon as an optical material, however, falls short of properties that are indispensable for high-performance photonic-electronic interfaces. In particular, the inversion symmetry of the silicon crystal lattice inhibits technically relevant second-order nonlinearities, thereby making electro-optic modulators challenging. To overcome these deficiencies, the silicon-organic hybrid (SOH) concept combines silicon photonic circuits with highly efficient organic electro-optic materials [2]. This approach leads to highly efficient devices, featuring voltage-length products well below 1 Vmm and energy consumptions of only a few fJ per bit [3]. The response of the electro-optic materials is ultra-fast and enables small-signal modulation at 100 GHz [4], generation of 100 Gbit/s on-of-keying (OOK) signals [5], and multi-level signaling at symbol rates of 64 GBd [6]. Moreover, we demonstrated generation of advanced modulation formats such as 16QAM at record-low energy consumptions and with symbol rates (bit rates) of up to 63 GBd (252 Gbit/s) transmitted on a single wavelength and a single polarization [7] – [9]. We further show that the extraordinarily low operating voltage of SOH modulators allows operation of the devices directly from standard output ports of field-programmable gate arrays (FPGA), without the need for external amplifiers or digital-to-analog converters. Such schemes can be used even if higher-order modulation formats such as 16QAM are to be generated [10]. SOH approach is a versatile concept that goes far beyond electro-optic modulators. We have also shown that compact and power-efficient SOH phase shifters can be realized by using liquid crystals (LC) as cladding materials [11]. We have further demonstrated that the concept of SOH integration can be transferred to plasmonic waveguide structures, leading to plasmonic-organic hybrid (POH) devices [12] that may open the route for modulation at THz frequencies [2].

Regarding WDM transmission based on optical frequency combs, our work aims at exploiting chip-scale comb sources that can be combined with SOH transmitters using monolithic or multi-chip integration concepts. Unlike carriers derived from a bank of individual laser modules, the tones of a comb are intrinsically equidistant in frequency, thereby enabling transmission at highest spectral efficiency. In addition, stochastic frequency variations of the carriers are strongly correlated, which enables efficient compensation of impairments caused by nonlinearities of the transmission fiber [13].

We performed a series of experiments to investigate the viability of chip-scale comb sources for WDM transmission. In a first set of experiments, we explore frequency comb generation using SOH electro-optic modulators, leading to line rates up to 1.152 Tbit/s on 9 optical carriers [14]. These devices enable large modulation depths at moderate drive voltages, thereby generating broadband frequency combs from a single continuous-wave (cw) laser line. Modulator-based comb generators lend themselves to monolithic co-integration with SOH transmitters. In a second set of experiments, we use gain-switching of an injection-locked laser diode to generate frequency combs [15]. These so-called gain-switched combs sources (GSCS) enable line rates of more than 2 Tbit/s using 24 comb lines as optical carriers. More recently, we have demonstrated that GSCS can not only act as light sources at the transmitter, but also as multi-wavelength local oscillators at the receiver [16]. In a third set of experiments, we use quantum-dash mode-locked laser diodes (MLLD) as frequency comb sources. These devices exhibit rather large optical linewidths, which either requires dedicated phase noise reduction schemes [17], self-homodyne detection [18], or digital phase tracking [19] to enable coherent communications with higher-order modulation formats at low symbol rates. At high symbol rates of, e.g., 40 GBd or more, carrier phase noise is less detrimental, and no additional measures are needed. In a WDM experiment with 52 channels, we demonstrate transmission of an aggregate line rate of 8.32 Tbit/s over a transmission distance of 75 km [19]. A fourth set of experiments is dedicated to exploiting Kerr nonlinearities in integrated silicon-nitride (SiN) microcavities for frequency comb generation. We demonstrate coherent communication using a Kerr frequency comb source, achieving line rates of up to 1.44 Tbit/s on 20 carriers [20]. We are currently working on increasing the transmission speed to data rates beyond 10 Tbit/s by using cavity-soliton Kerr combs that can provide hundreds of spectral carriers [21], [22]. Our experiments show that frequency comb generation in chip-scale devices represents a viable approach to terabit/s communications. GSCS, MLLD, and Kerr comb generators can be efficiently combined with SOH transmitters in optical multi-chip modules using the concept of photonic wire bonding [23], [24].

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