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Silicon-organic hybrid (SOH) integration and photonic multi-chip systems: Technologies for high-speed optical interconnects

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***Abstract*— Limitations of silicon photonics can be overcome by hybrid integration of silicon photonic or plasmonic circuits with organic materials or by photonic multi-chip systems. We give an overview on our recent progress regarding both silicon-organic hybrid (SOH) integration and multi-chip integration enabled by photonic wire bonding.**

Keywords — Silicon photonics, silicon-organic hybrid (SOH) integration, plasmonic-organic hybrid (SOH) integration, multi-chip integration, photonic wire bonding, optical interconnects

SUMMARY

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 devices: The indirect bandgap of crystalline silicon inhibits efficient light emission, and the inversion symmetry of the silicon crystal lattice prevents second-order optical nonlinearities, thereby making electro-optic modulators challenging. Our research focusses on hybrid integration concepts, which combine silicon photonic circuits with other material systems that provide complementary optical properties. In this paper, we give an overview on our recent progress in the fields of silicon-based hybrid integration and of photonic multi-chip integration.

To enable efficient electro-optic modulators on the silicon photonic platform, we exploit the concept of silicon-organic hybrid (SOH) integration that combines nanophotonic silicon waveguides with organic cladding materials [2] – [15]. This approach [2] leads to highly efficient devices, featuring energy consumptions of only a few fJ per bit [3], [4]. The response of the electro-optic materials is ultra-fast and enables small-signal modulation at 100 GHz [5], generation of 100 Gbit/s on-of-keying (OOK) signals [6], and symbol rates of 64 GBd for multi-level signaling [7]. Moreover, we demonstrated generation of advanced modulation formats such as 16QAM using in-phase-quadrature (IQ-)modulators with record-low energy consumption and symbol rates (bit rates) of up to 40 GBd (160 Gbit/s) [8], [9]. We further show that the extraordinarily low operating voltage of SOH modulators allows operation of these devices directly from standard output ports of field-programmable gate arrays (FPGA), without the need for external amplifiers and digital-to-analog converters. Such schemes can be used even if higher-order modulation formats such as 16QAM are to be generated [10]. Moreover, we use SOH devices for generating broadband frequency combs, which are well suited as optical multi-wavelength sources for terabit/s transmission [11]. On the long run, organic electro-optic materials might be replaced by second-order nonlinear metamaterials that exploit highly stable inorganic ABC-type nanolaminates fabricated by atomic-layer deposition (ALD) [12].

The SOH approach is a versatile concept that goes far beyond electro-optic modulators. In particular, we have also shown that compact and power-efficient SOH phase shifters can realized by using liquid crystals (LC) as cladding materials [13]. Moreover, optically pumped lasers have been demonstrated on the silicon photonic platform by using SOH waveguides that are based on dye-doped cladding materials [14]. These devices can only be operated in pulsed mode and lend themselves as sources in optical biosensors. We have also shown that the concept of SOH integration can be transferred to plasmonic waveguide structures, leading to plasmonic-organic hybrid (POH) devices [15]. We have demonstrated POH Mach-Zehnder modulators that feature a flat frequency response up to at least 65 GHz. Such devices and will potentially open the route for modulation at THz frequencies [15].

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The concepts of SOH and POH integration are complemented by photonic multi-chip integration that exploits photonic wire bonding [16] for assembling photonic systems from discrete dies fabricated on different material platforms [17], [18]. We have introduced photonic wire bonding and demonstrated its viability for chip-chip [16], [18] and fiber-chip [17] interfaces. The concept enables, e.g., hybrid multi-chip integration of silicon photonic circuitry along with InP-based light sources [18]. We believe that hybrid integration and photonic multi-chip systems are key concepts for highly scalable terabit/s photonic transceiver systems.

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