Integrated photonics for on-chip signaling

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On-chip terabit-scale digital signal transmission and low-distortion analog signal transmission can be achieved with favorable performance using ultra-compact silicon photonic devices.

Chip-scale optical interconnections based on photonic integrated circuits offer many advantages over electrical interconnections. These advantages include relaxed interconnection latency, wide bandwidth, high resistance to electromagnetic interference, and low power consumption. Silicon photonics represents a promising technology with which to address the ever-increasing challenges of future on-chip optical interconnections. Their compactness enables high-density integration and their compatibility with CMOS platforms should enable low-cost mass production. On-chip signaling with digital and analog modulation signals using ultra-compact integrated photonic devices represents one of the key technologies on the road to chip-scale optical interconnections.

To demonstrate the on-chip signaling of advanced multi-carrier multi-level modulation signals, we employed silicon microring resonators and silicon vertical slot waveguides. These waveguides were fabricated by electron beam lithography and inductively coupled plasma etching on a silicon-on-insulator wafer. Figures 1(a–d) show scanning electron microscope (SEM) images of the waveguide cross-section, microring structure, coupling region, and grating coupler, respectively. Using these silicon microring resonators, we were able to demonstrate on-chip data transmission with advanced multi-carrier multi-level modulation signals (e.g., orthogonal frequency division multiplexing based on offset quadrature amplitude modulation, OFDM/OQAM). Low-penalty data transmission of OFDM/OQAM at modulation orders of 64, 128, 256, and 512 (64-QAM, 128-QAM, 256-QAM, and 512-QAM) were achieved. The measured bit error rate (BER) curves as a function of received optical signal-to-noise ratio (OSNR) for orthogonal frequency division multiplexing based on offset quadrature amplitude modulation (OFDM/OQAM) m-QAM (m-ary QAM, where m=64, 128, 256, or 512) signal transmission through the silicon microring resonators for (e) 64-QAM and (f) 512-QAM. B-to-B: Back-to-back (i.e., measured result before transmitting through the system). Aft. Tran: After transmission (i.e., measured result after transmitting through the system). FEC: Forward error correction. EFEC: Enhanced FEC. Si: Silicon. SiO₂: Silicon dioxide.

Figure 1. Scanning electron microscope (SEM) images of (a) the waveguide cross-section, (b) the microring, (c) the coupling region between the bus waveguide and the bending waveguide, and (d) the grating coupler. Bit error rate (BER) vs. received optical signal-to-noise ratio (OSNR) for orthogonal frequency division multiplexing based on offset quadrature amplitude modulation (OFDM/OQAM) m-QAM (m-ary QAM, where m=64, 128, 256, or 512) signal transmission through the silicon microring resonators for (e) 64-QAM and (f) 512-QAM. B-to-B: Back-to-back (i.e., measured result before transmitting through the system). Aft. Tran: After transmission (i.e., measured result after transmitting through the system). FEC: Forward error correction. EFEC: Enhanced FEC. Si: Silicon. SiO₂: Silicon dioxide.
Figure 2. SEM images of the (a) grating coupler, (b) mode converter between strip waveguide and slot waveguide, (c) bending region, and (d) slot region of the silicon vertical slot waveguide. Experimental results for on-chip terabit-scale signal transmission: (e) output spectrum of the ultra-wide-bandwidth 1.8Tbit/s (161 WDM, 11.2Gbit/s OFDM 16-QAM) signals after transmission through the silicon vertical slot waveguide; (f) BER performance for all 161 WDM channels.

3.3dB at a BER of $2 \times 10^{-2}$ for 512-QAM (the threshold for the 20% FEC overhead). Figure 2(a–d) shows the SEM images of the grating coupler, mode converter between strip and slot waveguides, the bending region, and the slot region of the silicon vertical slot waveguide. Using the silicon vertical slot waveguides, we realized data transmission of wavelength-division multiplexed (WDM) OFDM 16-QAM signals. Additionally, we achieved ultra-wide-bandwidth 1.8Tbit/s (161 WDM, 11.2Gbit/s OFDM 16-QAM) data transmission through 1, 2, 3.1, and 12.2mm-long silicon vertical slot waveguides: see Figure 2(e) and (f). After propagating through these waveguides, all 161 WDM channels achieved a BER of less than $1 \times 10^{-3}$. We also designed and fabricated a vertical hybrid plasmonic waveguide assisted by two tapers, allowing efficient coupling between the hybrid plasmonic and dielectric modes. We achieved successful on-chip 1.8Tbit/s (161 WDM channel, 11.2Gbit/s OFDM 16-QAM) signaling through this waveguide.

In addition to on-chip signaling of advanced modulation signals, we were able to experimentally evaluate the on-chip analog signaling performance in silicon strip waveguides, microring resonators, and photonic crystal cavities. We analyzed the performance of on-chip analog signal transmission using the silicon strip waveguides. Slight degradations of second- and third-order harmonic distortion (SHD and THD, respectively), and of second- and third-order intermodulation were observed with the increase of waveguide length and optical input power. These impairments may have been induced by nonlinearities, such as two-photon absorption and free-carrier absorption. The resonance of the silicon microring resonator and photonic crystal cavity causes a notch power transfer function at the resonance wavelength (i.e., notch filtering): see insets of Figure 3(c) and (d). When the input signal wavelength falls into the 3dB bandwidth of the microring resonator and photonic crystal cavity, especially near the notch resonance wavelength, we observed a reduction of the spurious-free dynamic range (the radio frequency—RF—input power range at the left and right boundaries of which the fundamental RF power and SHD/THD power are equal to the noise floor). This shows that the analog signal transmission performance through the microring resonators and photonic crystal cavities is mainly affected by the notch filtering effect.

In summary, we have successfully demonstrated on-chip signaling with ultra-compact integrated silicon photonic devices. We achieved on-chip terabit-scale digital signal transmission and low-distortion analog signal transmission with favorable performance. With increasing demand for chip-scale digital/analog signaling and recent progress in the fabrication of nanophotonic devices, these experiments have shown...
Figure 3. SEM images of (a) the silicon microring resonator and (b) the photonic crystal cavity. Measured output power of radio frequency (RF) carrier and second-order and third-order harmonic distortions (SHD and THD, respectively) as a function of RF input power for (c) the microring resonator and (d) the photonic crystal cavity. 6, 7

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great potential for on-chip photonic interconnection applications. Besides on-chip signaling, we are also working toward on-chip photonic signal processing functions—such as on-chip wavelength conversion, multiplexing/demultiplexing, data exchange, computing and coding/decoding—which are widely desired in the development of chip-scale photonic interconnection applications.