Ultra-Compact Coherent Receiver Based on Hybrid Integration on Silicon


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Abstract: A coherent receiver based on silicon photonics is presented. Its performance is confirmed by single-channel and WDM transmission tests with PM-QPSK modulation at 28 Gbaud up to 4800 km. The packaged core is very compact with dimensions of 6 mm × 8 mm.

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1. Introduction
In response to the increasing demand for bandwidth, telecommunication systems operating at 100 Gb/s are now deployed in long-haul links. In particular, larger bandwidth is achieved not only using higher data rates but also using increased spectral efficiency thanks to advanced modulation formats, especially in a coherent detection scheme. While increasing the physical density, minimizing the power consumption, heat dissipation and component size becomes a stringent requirement. Photonic integration is seen as the most promising avenue to address these problems. A coherent receiver based on indium phosphide has been demonstrated recently [1]. In particular, integration on silicon photonics (SiP) attracts enormous interest due to its potential for low cost, high level of integration and ultra-small footprint [2]. However, the potential of SiP for fabricating ultra-small footprint devices has not been fully demonstrated yet through a completely packaged device.

In this paper, a polarization diversity coherent receiver is demonstrated using hybrid integration using silicon photonics. The potential for a very small footprint component is demonstrated by compact packaging. Excellent performance is confirmed by a transmission through a link of 4800 km of SMF 28e+ fiber.

2. Design
The schematic of the coherent receiver is shown in the left part of Fig. 1. The SiP chip is used for the passive part of the receiver. The optical circuit has been fabricated at ePIXfab and is based on 500 nm × 220 nm strip waveguides. For each polarization, a 2×4 MMI (multimode interference) coupler serves at mixing with the proper relative phases and splitting, the optical signal carrying the data with an optical local oscillator (LO). A standard single-mode fiber polished at an angle close to 45° is used to couple the light from the signal port to the SiP chip through a 2D surface grating coupler which also provides the polarization splitting [3]. A polarization maintaining fiber, also polished close to 45°, is used to couple the light from the LO port to the SiP chip through a 1D surface grating coupler [4]. The light emerging from the two arms of the 2D grating coupler and corresponding to nearly orthogonal polarizations is sent to the two 2×4 MMI couplers. The light from the LO port is evenly split using a 1×2 MMI coupler and sent to the other input of the 2×4 MMI couplers. The outputs of each MMI couplers are connected to 1D surface grating couplers allowing the light to emerge out of the chip. Two 1×4 photodiode arrays are then flip-chip bonded on top of the SiP chip which is beforehand gold metallized. Capacitors are mounted on top of the SiP chip and wirebonded to the photodiode cathodes for biasing purpose. The optical chip is fixed on a ceramic substrate which allows to properly carry the RF signals. Two dual differential trans-impedance amplifiers (TIAs) are also

Fig. 1. Schematics of the coherent receiver (left) and picture of the coherent receiver assembly (right).
attached on the ceramic in close proximity to the SiP chip. Their inputs are wirebonded to the photodiode anodes. Each differential TIA is connected to two photodiodes collecting the light from two out-of-phase outputs of a MMI coupler, thus providing balanced detection. The overall assembly is very compact with an area of only 6 mm × 8 mm as seen in the assembly shown in the right part of Fig. 1.

3. Optical characterization
The quadrature provided by the two MMI couplers was verified by comparing the phase of the electrical signals at the TIA outputs. These were produced by the beating between two continuous-wave (CW) optical signals injected at the signal and LO ports when their frequency difference was adjusted between 200 MHz and 1 GHz. The signals were found to be in quadrature with an error less than 4.9° over the C-band. The common mode rejection ratio (CMRR), defined as the difference between the photocurrents of a balanced detector divided by their sum, was also measured at 1545 nm for each pair of input and output ports [5]. A CMRR value of −15 dB was obtained in the worst case. The overall small signal frequency response of the device is shown in Fig. 2 where a 3 dB bandwidth of 22 GHz or higher is seen. This response includes the photodiodes, the TIA and the RF lines on the ceramic. It is thus confirmed that the flip-chip bonding of the photodiodes does not degrade the RF performance.

4. System tests
To confirm its proper functionality, the coherent receiver was used in transmission experiments using a PM-QPSK modulation at 28 Gbaud. The LO power was set to 15.5 dBm in all cases. Fig. 3 shows a schematic of the setup.

In a first experiment, the elements inside the red dotted lines in Fig. 3 were removed. A CW light at 1553 nm was launched into the QPSK modulator. A polarization beam splitter, a delay line and a polarization combiner were used to emulate polarization division multiplexed (PDM) transmission. The transmission link consisted of a 320 km recirculating loop composed of four sections of 80 km of SMF 28e+ low-loss fiber each followed by an erbium doped fiber amplifier (EDFA). The transmitted signal was received using the coherent receiver back-to-back and after propagating through 5, 10 and 15 loops corresponding to propagation distances of 1600, 3200 and 4800 km respectively. The electrical signals from the coherent receiver were digitized using two real-time oscilloscopes model DSO-X93204A from Agilent and the gain in the receiver’s TIAs was adjusted such as to provide differential voltage output swings of 640 mV. The scale of the oscilloscope was adjusted to 40 mV/div in order for the 320 mV single-ended output swing to cover its 8-bit analog-to-digital conversion range. Digital signal processing (DSP) was performed off-line and a Q²-factor was obtained for each propagation distance. The DSP contained algorithms for imbalance compensation, frequency offset compensation, chromatic dispersion compensation, polarization demultiplexing, polarization mode dispersion compensation and phase noise compensation. A variable optical attenuator was also used to vary the optical power at the receiver input. The left part of Fig. 4 shows the resulting Q²-factor for different propagation distances and received optical powers. The optical signal-to-noise ratios (OSNR) were measured to be 21.2, 19.3 and 17.7 dB after 1600, 3200 and 4800 km of propagation respectively. Also shown in Fig. 4 are the receiver’s eye diagrams for each propagation distance.
in the inserts of Fig. 4 are the constellations for signal powers of -3 dBm. Considering a forward error correction (FEC) limit of 9.2 dB for the $Q^2$-factor, the results shown in the left part of Fig. 4 indicates an error-free transmission up to 4800 km for a signal optical power down to $-21$ dBm.

In a second experiment, the demultiplexing capability of the coherent receiver was investigated [6]. In that case, all the components shown in Fig. 3 were used. Sixteen signals at wavelengths from 1551.7 to 1557.8 nm on a 50 GHz grid were bulk modulated and sent to the transmission link. An optical filter having variable bandwidth and central wavelength was inserted in front of the coherent receiver. This filter was adjusted to control the number of optical carriers sent to the coherent receiver. As for the single channel experiment, the signal power was varied using the variable optical attenuator. Results are shown in the right part of Fig. 4 for propagation distances of 1600 and 3200 km while the optical filter is adjusted to transmit 1, 9 or all 16 channels. The presence of adjacent optical carriers at the coherent receiver input was found to cause no degradation as compared to the case where they are filtered out by the optical filter. The wavelength of the local oscillator alone can thus be used to select the optical signal to be detected in a totally colorless WDM reception.

5. Conclusion
An ultra-compact coherent receiver based on hybrid integration on silicon was realized. Its performance was demonstrated by a PM-QPSK transmission at 28 Gbaud up to 4800 km. The ability of the receiver to select an optical carrier among 16 channels was also demonstrated in a colorless experiment.

The present approach allows a significant device size reduction as compared to the present state-of-the-art as illustrated in Fig. 5 where the package size of 18 mm is estimated from the core assembly footprint and considering achievable RF fan-out and package. The small footprint is also promising for its potential use in a compact package such as a CFP module. It also opens the door to further integration, noteworthy in a multi-channel reception.

6. References