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Cost-effective 200-Gbps/λ coherent PON enabled by DFB lasers and a pilot-based carrier recovery

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The rising demand for services such as Internet of Things and cloud networking has propelled the optical access network industry to explore new bandwidth acceleration solutions, in which passive optical networks (PONs) have become a key point-to-multipoint technology for last-mile connections between service providers and customers across various passive optical distribution networks. For predominant PON architectures, the core requirements include effective cost, simple structure, and compact footprint. To support PONs with data rates of 100 Gbits/s/λ and beyond, coherent sinking has become attractive due to its enhanced receiver power sensitivity and improved power budget through the incorporation of an optical local oscillator (LO) and robust digital signal processing (DSP). However, the significant costs associated with necessary optical components and DSP modules hinder the widespread adoption of coherent PONs, especially considering the costly optical sources with narrow linewidths deployed in both optical line terminals (OLTs) and optical network units (ONUs) [1]. To this end, an efficient approach to achieve cost savings and facilitate smooth upgrades within the legacy architecture is to substitute expensive high-quality laser sources, such as external cavity lasers (ECLs) with lower-cost alternatives. Thus, low-cost distributed feedback lasers (DFBs) present a promising solution as long as the inherent power penalties associated with greater laser phase noise (PN) can be properly addressed with acceptable complexity. In addition to the PON architecture, the simplification of the DSP equipped also remains active areas of this research field. In this study, we for the first time realize and experimentally demonstrate a cost-effective coherent PON operating at 200 Gbits/s/λ, in which solely DFBs are specially deployed for cost saving and the existing legacy PON structure is leveraged for a seamless upgrade. In high-speed coherent PON systems employing digital subcarrier multiplexing (DScM) QPSK, we propose a scheme that effectively addresses the significant PN using straightforward DSP algorithms. These include frequency-domain pilot tone-based frequency offset equalization (FPT-FOE) and carrier phase recovery (FPT-CPR) [2, 3], and pre-emphasis to mitigate the bandwidth limitations of optoelectronic devices. Through our scheme, we achieve a power budget of 29.9 dB at the 7% hard-decision forward error correction (HD-FEC) bit error rate (BER) threshold of 3.8×10^{-3}, after 24.5 km of standard single-mode fiber (SSMF) transmission using DFBs, with negligible performance differences from the ECL configuration. Besides, the overall DSP complexity can be effectively reduced by QPSK demonstrating superior robustness against nonlinearity, and by a sliding window averaging (SWA) method to further simplify the low-pass filter (LPF) implementation required for FPT-CPR [3].

Methodology. According to the model based on the Wiener stochastic process, the PN intensity is proportional to the sum of the linewidths of the lasers at both the OLT and the ONUs. Therefore, to specifically address the increased PN associated with cost-effective DFBs that have linewidths at least ten times greater than those of ECLs, we introduce a bifunctional FPT generated in the optical domain into a DScM signal employing QPSK. For the DScM-QPSK, two sub-bands are set to create a 1-GHz guard interval, which is specifically designed to effectively mitigate crosstalk between the net sub-band signals and the inserted FPT. The generation of the desired FPT is implemented by a residual optical carrier (ROC) which is realized by slightly adjusting the optical modulator bias away from the null point, namely the suppression point of the optical carrier. The FPT facilitates both FOE and CPR since it experiences the same FO and PN as the signal bands after mixing with the LO at the receiver. In detail, FPT-FOE involves identifying the peak in the electrical spectrum by fast Fourier transformation under the assumption that the lasers are quasi-static and restoring it to the direct current component, where the FPT is intentionally inserted. The FPT along with PN is subsequently extracted using an LPF for the following FPT-CPR. Finally, the FPT is conjugated and multiplied by the signal to remove PN as

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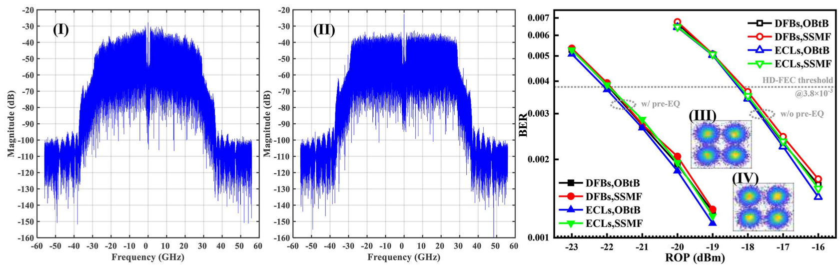

Figure 1 (Color online) BER versus ROP. Electrical spectrum with DFBs (I) without pre-emphasis at ROP of −16 dBm and (II) with pre-emphasis at ROP of −19 dBm; constellation diagram at ROP of −22 dBm after DD-LMS with (III) DFBs and (IV) ECLs.

$s_{\mathrm{CPR}} = s \times (|s_{\mathrm{PT}}|/s_{\mathrm{PT}})$. s_{CPR}, s, and s_{PT} are the signal after FPT-CPR, the post-FOE signal with PN, and the filtered FPT with PN in the time domain, respectively. Additionally, to effectively reduce the implementation complexity of an LPF with an MHz-class bandwidth, particularly when the sampling rate is in the tens of GHz range, we introduce a straightforward method of SWA [3] to emulate an LPF with equal tap coefficients through recursive operations. Apply a sliding window of length L to the received data after FPT-FOE, and the output of the LPF can be expressed as $s_{\mathrm{PT}}(k) = \sum_{i=(k-1)+1}^{(k-1)+L} s(i)/L$, where k is the index of the sliding window.

Experimental setup and results. At the optical line terminal (OLT), a digital pre-emphasized DScM-QPSK signal was generated by the DSP modules including QPSK mapping from a pseudo-random binary sequence, pre-emphasis, root-raised-cosine filtering with a roll-off factor of 0.01, upsampling, digital conversion, and resampling in order. The resulting 56-GBaud electrical DScM-QPSK signal with a net symbol length of 65536, intended to drive an integrated in-phase/quadrature modulator (IQM), was output by an arbitrary waveform generator operating at 64 GSa/s with a 25-GHz 3-dB bandwidth and subsequently boosted by an electrical amplifier. For the optical carrier, a continuous lightwave emitted by a commercial laser operating at 1536.8 nm with 9.6-dBm output power was directed to the IQM. Notably, in our experiment, we selected either a pair of ECLs with 3-dB linewidths of less than 100 kHz or a pair of DFBs with 4.2 MHz linewidths as the laser sources for both the OLT and ONU, respectively. Following the IQM, the generated optical signal was delivered to a polarization multiplexer with a ∼2-m optical delay line to emulate an optical dual-polarization (DP) signal. The signal at the launch power of 8 dBm controlled by an EDFA was transmitted through a 24.5-km SSMF with an average loss of 0.21 dB/km at 1550 nm. After passing through a variable optical attenuator utilized to account for the split loss and adjust the received optical power (ROP) for power budget estimation, the received optical DP signal was sent to a DP integrated coherent receiver with a 34-GHz bandwidth at the ONU, where an LO at 1536.8 nm was sourced from the other laser in the same type of laser pair. After analog-to-digital conversion by the digital phosphor oscilloscope with a 36-GHz bandwidth and an 80-GSa/s sampling rate, the captured signal was injected into the offline DSP block, which included resampling, Gram-Schmidt orthogonalization, FPT-FOE and FPT-CPR, digital conversion, matched filtering, re-timing, 53-tap constant modulus algorithm (CMA) for de-multiplexing and inter-symbol interference mitigation, maximum-likelihood phase noise estimation (ML-PNE), synchronization, 31-tap decision-directed least-mean-square (DD-LMS) algorithm for transmitter-end skew compensation, de-mapping and BER calculation in order. Figure 1 presents a summary of the BER versus ROP. Note that the curves for the optical back-to-back (OBtB) link and the 24.5-km SSMF transmission exhibit minimal differences, suggesting negligible penalties associated with fiber nonlinearity. When pre-equalization is employed, a sensitivity improvement of approximately 3.75 dB can be achieved compared to the signals absent from pre-emphasis, measured at the 7% HD-FEC BER threshold. Intuitively, Figures 1(I) and (II) illustrate the electrical spectra for the DFB configurations at a similar BER. At the BER threshold, the power budget for the 56-Gbaud (net rate: 208.3 Gb/s) signal after 24.5-km SSMF transmission is calculated as 29.90 dB when DFBs are deployed, while it is 29.94 dB with ECLs. Furthermore, the performance differences between the DFB and ECL configurations are measured as less than 0.1 dB for both the OBtB and the SSMF cases. Additionally, the constellation diagrams obtained after DD-LMS for both laser configurations are shown as insets (III) and (IV), indicating comparable performance.

Complexity discussion. For the FPT-CPR implementation based on ROC, the primary differences in complexity between the conventional scheme and the simplified approach lie in the LPF realization. Unlike the conventional method, which employs a finite impulse response filter with a number of taps dependent on its bandwidth and the sampling rate, the SWA performs in a recursive manner, achieving savings of 3 orders of magnitude in real-valued multiplication calculations in our case.

Conclusion. We for the first time experimentally demonstrate a 200-Gbits/s/λ cost-effective coherent PON utilizing low-cost DFBs and leveraging the legacy PON architecture. We effectively address the significant PN caused by the economical DFBs with MHz-class linewidths, through advanced DSP techniques. Our scheme achieves a power budget of 29.9 dB at 7% HD-FEC BER threshold after 24.5-km SSMF transmission, comparable to that of the ECL configuration. We believe that our scheme lays a solid foundation for the ongoing research and development of 200G PON technology.

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