Full-Duplex, Polarisation-Independent Coherent Homodyne EML Transceiver

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Abstract. A conceptually simple coherent transceiver based on an externally modulated laser is proposed for virtual point-to-point transmission and experimentally evaluated for low-cost access applications. The analogue EML transceiver pair is shown to allow for full-duplex transmission and polarization-independent coherent reception with highly reduced optical layer complexity. The locking stability of the homodyne receiver is confirmed for the injection of 14 data channels and in presence of Rayleigh backscattering at 1 km of drop fibre. An unshared per-user data rate of 2.5 Gb/s is achieved for an optical loss budget of 36.3 dB, without the need for digital signal recovery.

1 Introduction

2048-ary signal constellations [1], spectral efficiencies of up to 1100 bits/s/Hz [2] and per-link capacities of 10 Pb/s – this shortlist of performance credentials renders coherent optics as the necessary step towards further performance scaling in short-reach networks. Coherent detection is considered as the most compelling approach to reach higher sensitivities [3], to introduce a high channel occupancy for the efficient use of precious optical transmission spectrum [4], and to gain access to advanced modulation formats [5]. On the other hand, its practical implementation begs the question as to whether coherent transceivers can be cost-effectively implemented. For example, optical access, as a representative cost-sensitive segment, demands single-fibre access and analogue RF electronics for its cost-unshared communication terminals. These requirements stand against the record performances stated introductorily [1-2], which have been obtained through the use of highly complex coherent transceivers.

In this work we endeavour a step towards ultra-lean coherent transceivers. We originate from a simple light source, an externally modulated laser (EML), and exploit its assets as a coherent homodyne receiver for virtual point-to-point links. In order to yield a full-duplex coherent optical pipe, we top this functionality by simultaneous data transmission over the same EML. Moreover, we introduce the required methods for polarisation-independent operation of this low-cost, full-duplex and analogue coherent homodyne transceiver and eventually prove its robustness to fibre backscattering.

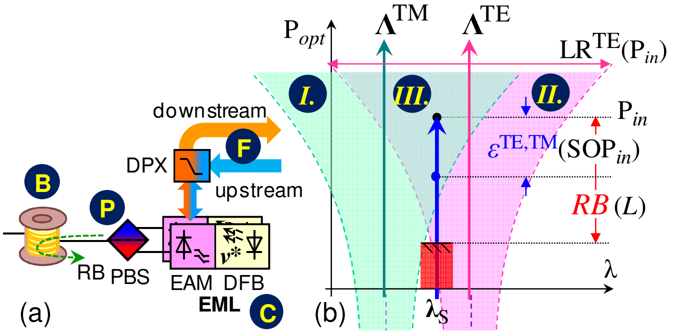

Fig. 1 (a) Coherent transceiver concept based on an EML pair and (b) spectral allocation of signal and independent LOs.

2. Methodology: Coherent EML transceiver

Coherent optics do not necessarily have to be complex. As a matter of fact, we have recently demonstrated that a simple EML can serve as coherent homodyne transceiver at the cost-sensitive tail-end sites of an optical network [6]. Figure 1(a) sketches the principal methodology and the context of the present work. The EML with its distributed feedback (DFB) laser and electro-absorption modulator (EAM) is exploited as a local oscillator (LO) and as a fast photodetector, respectively. Injection locking ensures that this coherent receiver (**C**) operates as homodyne detector, by synchronising the emission frequency of the DFB laser to that of the received optical signal λ_S. This process is compatible with low optical feed power levels. For example, for an injected optical signal P_{in} of -30 dBm, corresponding to an injection ratio of -37 dB between DFB laser power and incident signal, the locking range (LR) is 210 MHz and therefore much larger than the typical wavelength instability of a temperature-controlled laser. Additional phase-locked loops can enable injection ratios of less than -60 dB [7]. We will prove stable homodyne channel selection under a DWDM feed, even without digital signal recovery.

Full-duplex operation (**F**) is achieved through a paired electrical spectrum. A duplexer (DPX) in the RF domain performs the directional split between down- (DS) and upstream (US). A single opto-electronic device, the EML, remains to cover all required functions at the optical layer.

For practical applications, the received optical signal has to be aligned to the polarisation axis of the local oscillator of the EML. Polarisation-independent operation (**P**) can be obtained through diversity reception with two independent EML receivers, as it has been recently proven [8]. As Fig. 1(b) shows, the free-running LOs of the EMLs at Λ_{TE} and Λ_{TM} of the diversity arrangement feature independent locking characteristics, as indicated through the injection-level dependent, cone-shaped frequency locking ranges (regions *I* and *II*). For stable operation at a low received optical power P_{in}, the LOs need to be tuned in the vicinity of the data signal λ_S so that the particular locking ranges overlap (*III*). This is ensured through a micro-cooler that is co-packaged with the transistor-outline (TO) EMLs. In this way the LO emission frequency is kept within a range of ~20 MHz to the set point. Even though the optical injection to the EML is further reduced by the polarisation-selective extinction $\varepsilon_{TE,TM}$ of the polarizing beamsplitter (PBS) of the diversity receiver, the highly sensitive injection locking process allows for homodyne operation under an arbitrary input state-of-polarization (SOP_{in}). At the same time polarization-multiplexed upstream transmission is yielded.

On top of this, we experimentally prove the robustness to optical feedback (**B**) as it results from distributed Rayleigh backscattering (RB). In practical deployments, drop fibre lengths *L* in the kilometre range will lead to Rayleigh crosstalk from the transmitted signal, which in turn can impact the locking stability of the proposed coherent transceiver. We will first characterize the impact of RB and eventually confirm the correct operation of the proposed low-cost transceiver through data transmission measurements.

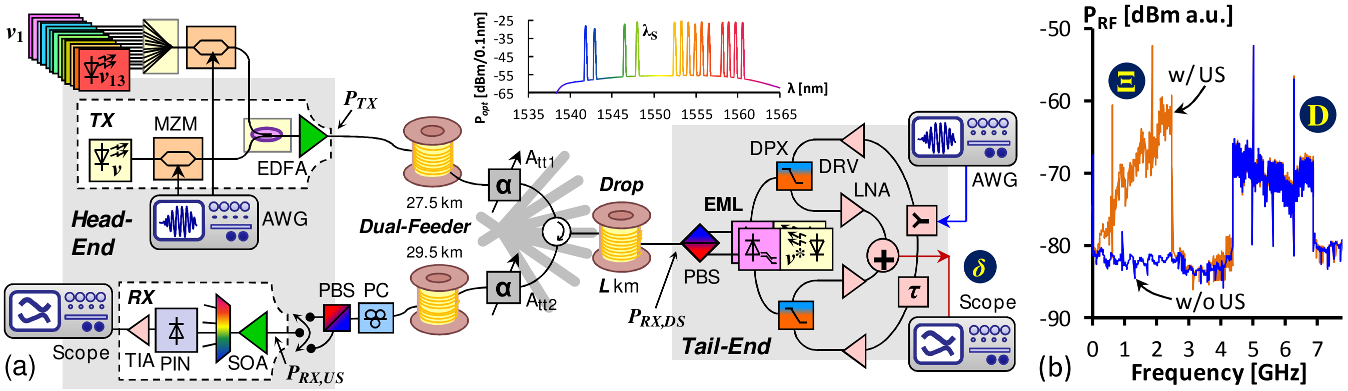

Fig. 2 (a) Experimental setup and DWDM drop signal. (b) Received downstream spectrum.

3 Experimental setup and Rayleigh noise

The experimental setup is presented in Fig. 2(a). At the head-end a 14-channel DWDM comb from 1542.14 to 1560.61 nm is modulated with double-sideband OFDM data signals. This downstream comb is launched with 3 dBm/λ and is transmitted through a dual-feeder, single-drop distribution network. The directional split towards the head-end terminal is facilitated in the optical domain through a circulator, which separates down- and upstream. Variable attenuators (A_{tt1}, A_{tt2}) have been inserted in the distribution network to emulate a passive power splitter. While the feeder spans have been fixed with 27.5 and 29.5 km, the length *L* of the drop span has been varied to investigate RB effects.

The tail-end coherent transceiver locks on the target channel at 1547.72 nm. The RF duplexer, which facilitates the directional split at the tail-end, had an edge frequency of 3 GHz to separate down- and upstream bands. Low-noise amplifiers (LNA) have been used as electrical receiver front-ends. Although this is sub-optimal in terms of noise performance, it enables to prove the concept. The dismissal of packaged components would allow for a low-capacitance co-integration with a transimpedance amplifier (TIA).

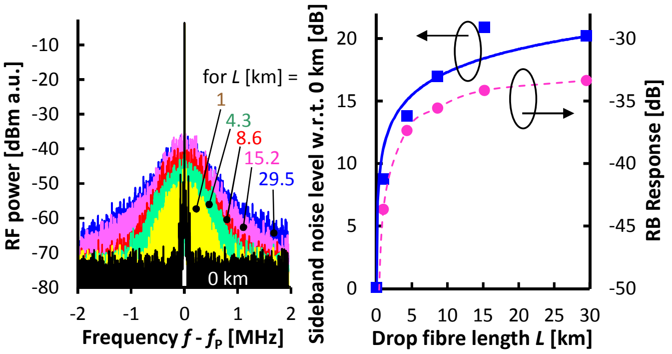

Fig. 3 Pilot tone spectrum and Rayleigh noise.

The polarisation-multiplexed upstream data is received through a SOA-pre-amplified PIN receiver. Both polarization tributaries have been separately acquired through manual selection of the polarization plane (PC).
The impact of Rayleigh noise was characterised for pilot tone reception at f_P = 5.2 GHz. Figure 3 shows the pilot spectrum for various drop span lengths *L* and a constant injection level of -30 dBm to the coherent receiver. The sideband noise power (■) of the pilot tone, relative to an absent drop fibre, increases sharply at the first 10 km and saturates at longer reach. This behaviour aligns well with the RB response (i.e., the ratio of backscattered to launched optical power) of a standard single-mode fibre (●). The receiver remained frequency-locked for various drop lengths, as it is evidenced through the sharp spectral line at the pilot tone frequency.

4 Results: Full-duplex signal transmission

A drop fibre length of 1 km has been chosen to evaluate the data transmission performance in a realistic deployment scenario. OFDM signals with 128 adaptively modulated sub-carriers over a 2.5 GHz bandwidth have been chosen for data transmission. According to the frequency division duplex scheme the paired spectra for down- and upstream signals are centred at 5.65 and 1.25 GHz, respectively.
Figure 2(b) shows the received downstream spectra at point *δ* in the setup. In virtue of coherent homodyne reception the double-sideband passband OFDM signal of the downstream (D) does neither show strong fading nor is it washed out. There is no instability due to the co-injected DWDM comb. When the upstream is switched on, the good suppression of the adjacent lower upstream frequency band by the DPX results in a moderate crosstalk signature (Ξ) that does not spectrally overlap with the downstream signal. This enables full-duplex operation with a single EML device.

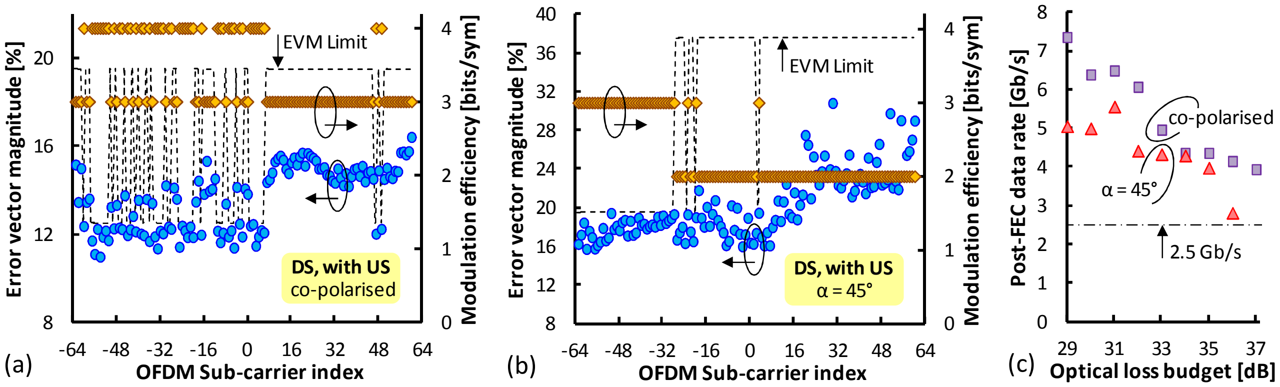

Fig. 4 Downstream EVM and modulation efficiency at a loss budget of 29 dB for (a) co-polarized input signal and (b) an input SOP at an azimuth of 45°. (c) Dependence of the downstream data rate on the optical budget.

The downstream EVM performance with simultaneous upstream transmission is shown in Fig. 4(a) for an input signal that is co-polarized with the LO of the EML and in Fig. 4(b) for an input SOP with an azimuth of α = 45°. EVM (●) and bit loading (◆) are reported for an optical loss budget of 29 dB between head- and tail-end. The average modulation efficiency is 3.4 and 2.3 bits/symbol, respectively, leading to post-FEC data rates of 7.4 and 5.1 Gb/s when considering the 7% overhead for hard-decision FEC. The difference in performance results from the lower signal-to-noise ratio at α = 45° due to the 3-dB penalty when summing the detected polarization tributaries. These results prove that data reception can be performed without polarization control.

Figure 4(c) presents the post-FEC data rate as a function of the optical loss budget for both, the co-polarized input (■) and at α = 45° (◆). Measurements are obtained through adjustment of the variable attenuator A_{tt1} at the optical distribution network. A virtual point-to-point data rate of 2.5 Gb/s can be achieved for a loss budget of 36.3 dB. This proves better than the unshared data-rate of NG-PON2. Table 1 provides a direct comparison, which also includes the sub-system complexity and the spectral resource mobilisation.

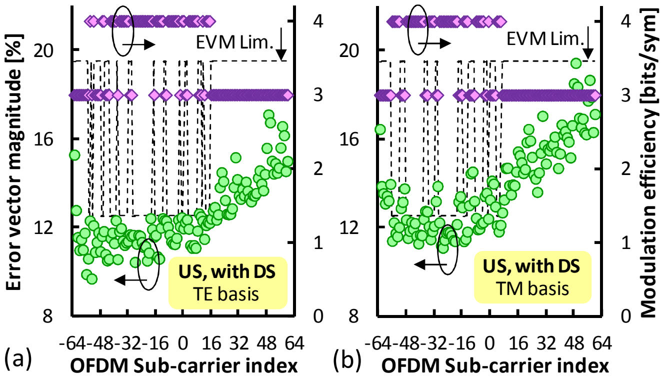

Fig. 5 Upstream EVM and modulation efficiency.

The upstream performance with simultaneous downstream transmission is reported in Fig. 5. EVM measurements (●) of both polarization tributaries are presented after polarization alignment to the head-end receiver. The modulation efficiencies (◆) for the tributaries are 3.4 and 3.35 bits/symbol at a loss budget of 20 dB.

Characteristic	**NG-PON2**	**Coherent EML**
Transmitters Receivers	4× EML 4× APD	2× EML
Spectral utilization (64 users)	4× DWDM 100G + 4× DWDM 200G = 1200 GHz (DS+US)	883 GHz (assuming ultra-dense WDM)
Unshared per-user data rate	625 Mb/s at 35 dB budget	2.5 Gb/s at 36.3 dB budget

Table 1. Comparison between NG-PON2 and virtual point-to-point transmission using the proposed coherent transceiver.

5 Conclusion

We have proven, for the first time, a polarisation-independent full-duplex coherent transceiver based on a dual-EML configuration. Homodyne reception of double-sideband modulated OFDM signals with simultaneous upstream transmission has been shown for 2.5 Gb/s over 36.3 dB loss budget and 28.5 km reach. Robustness to Rayleigh scattering at the optical port of the EML transceiver has been validated for a 1-km drop fibre. No digital signal processing functions have been applied besides OFDM demodulation.

6 Acknowledgements

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7 References

[1] Beppu, S., Kasai, K., Yoshida, M., Nakazawa, M.: '2048 QAM (66 Gbit/s) single-carrier coherent optical transmission over 150 km with a potential SE of 15.3 bit/s/Hz', OSA Opt. Expr., 2015, 23, (4), pp. 4960–4969

[2] Soma, D., Wakayama, Y., Beppu, S., et al.: '10.16-Peta-B/s Dense SDM/WDM Transmission Over 6-Mode 19-Core Fiber Across the C+L Band', IEEE/OSA J. Lightwave Technol., 2018, 36, (6), pp. 1362–1368

[3] Shahpari, A., Ferreira, R.M., Luis, R.S., et al.: 'Coherent Access: A Review', IEEE/OSA J. Lightwave Technol., 2017, 35, (4), pp. 1050–1058

[4] Lavery, D., Gerard, T., Erkilinc, S., et al.: 'Opportunities for Optical Access Network Transceivers Beyond OOK', IEEE/OSA J. Opt. Commun. Netw., 2019, 11, (2), pp. 186–195
[5] Mecozzi, A., Antonelli, C., Shtaif, M.: 'Kramers–Kronig coherent receiver', OSA Optica, 2016, 3, (11), pp. 1220–1227
[6] Schrenk, B., Karinou, F.: 'A Coherent Homodyne TO-Can Transceiver as Simple as an EML', IEEE/OSA J. Lightwave Technol., 2019, 37, (2), pp. 555–561
[7] Wu, D.S., Slavik, R., Marra, G., et al.: 'Direct Selection and Amplification of Individual Narrowly Spaced Optical Comb Modes Via Injection Locking: Design and Characterization', IEEE/OSA J. Lightwave Technol., 2013, 31, (14), pp. 2287–2295
[8] Schrenk, B., Karinou, F.: 'Polarization-Immune Coherent Homodyne Receiver Enabled by a Tandem of TO-can EMLs', Proc. Europ. Conf. Opt. Comm., Rome, Italy, Sep. 2018, We4G.2