Simple Single-Laser Coherent Transceiver based on Low-Cost D-EML for Edge Networks

Miquel Masanas, Victor Polo, Josep Prat

***Abstract*— In this work we demonstrate single-laser, D-EML based coherent transceivers which transmit and simultaneously receive optical single sideband modulations through a phase noise cancelling scheme, leading to phase-noise and frequency-detuning clean signals. We use QPSK and 16-QAM modulations over a 500 Mbaud signal, reaching 1 Gbps and 2 Gbps respectively, with sensitivities as low as -53 and -40 dBm with unmodulated local oscillator, respectively, and -35 dBm for QPSK with modulated local oscillator, achieving high sensitivity coherent UD-WDM for analog radio over fiber and mobile fronthaul over passive optical networks.**

***Index Terms*— Coherent radio-over-fiber (CRoF), coherent mobile Fronthaul, dual-electroabsorption-modulated laser (D-EML), optical communications, optical sources, optical single sideband (OSSB), phase-noise cancelling, fiber-wireless, mobile Fronthaul, radio-over-fiber (RoF).**

I. Introduction

The growing amount of connected devices demanding increased bandwidths (BWs) and reduced deterministic latency, require the supporting backhaul and fronthaul networks to deliver better performance and power budgets while being cost-effective, energy-efficient and low-footprint. In particular, the starker requirements of next-generation radio access networks include linearity, integration and low phase noise [1]. To reduce the cost of the network, point-to-multipoint architectures have been proposed. However, they introduce high splitting loss and result in indeterministic latencies when using time-division multiplexing. Optical coherent detection, along with ultra-dense wavelength division multiplexing (UD-WDM) has been thoroughly studied as a tool to provide the required extended power budget, allocated bandwidth and spectral efficiency [2]. Conventional coherent typically uses digital signal processing (DSP) and feed-back loops to lock the local oscillator (LO) and the incoming signals' phases, and usually needs either two lasers per termination or two fibers per link, increasing cost and complexity. On the other hand, scenarios such as massive deployment of sensors or distributed antenna systems, proposed for both 5G and 6G Fronthaul [3], consider analog radio-over-fiber (RoF) implementations to achieve lower latency, power consumption, development timing and costs.

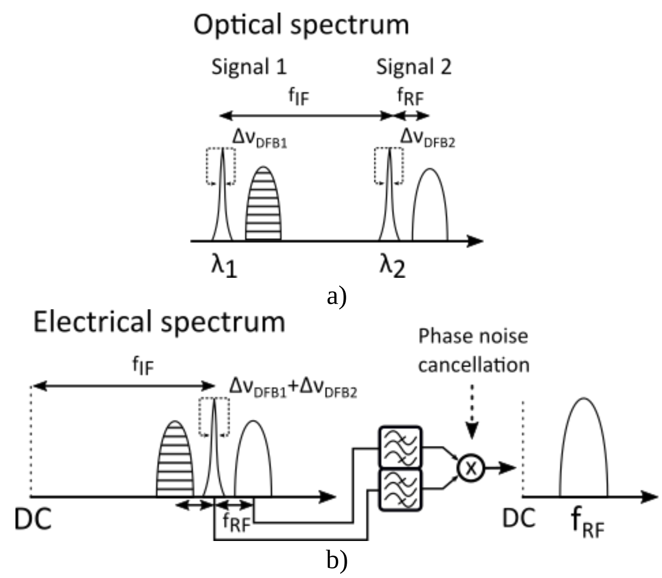


Fig. 1: a) The signal 1 (stripes) acts as a LO for the detection of signal 2 (blank). Both channels are modulated in RF with f_{RF}. **b)** After optical heterodyne detection, bandpass filters separate the carrier and the data, and an electrical heterodyne mixing.

However, RF transmission is not typically suited for coherent detection, because of the phase noise added by the laser sources. In [4] we proposed to use heterodyne detection of a full-carrier optical single sideband (FC-OSSB) to perform a phase-noise cancelling (PNC) scheme, enabling analog RF mobile back-hauling with a coherent receiver (Rx). At the transmitter (Tx) a low cost and low footprint dual electroabsorption modulated laser (D-EML) performs both phase and amplitude modulation as in [4], generating the FC-OSSB signal. At the heterodyne Rx we retrieve phase information from the unmodulated carrier to analogically cancel phase and frequency impairments. This achieves continuous data streams, highly linear UD-WDM systems with increased power budgets and spectral efficiency.

In this work, we expand on the aforementioned scheme and demonstrate a single-laser RoF heterodyne transceiver which reuses a split of the transmitted signal as the LO. We test the proposal for both QPSK and 16-QAM 500 Mbaud modulations

Manuscript received XX, XXX; revised XXX; accepted XXX. Date of publication XXX; date of current version XXXX. This work has been partially funded by the Spanish Ministry of Science and Innovation, grant VERSONET (Versatile Optical Coherent Network), code RTI2018-097051. *(Corresponding author: Miquel Masanas.)*
The authors are with the Department of Signal Theory and Communications, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain (e-mail: miquel.masanas@upc.edu; victor.polo@upc.edu; jprat@tsc.upc.edu).
Color versions of one or more figures in this letter are available at XXXXXXXXXXXX

Digital Object Identifier XXXXXXXX

over a 1 GHz radio frequency, resulting in bit rates of 1 and 2 Gbps respectively.

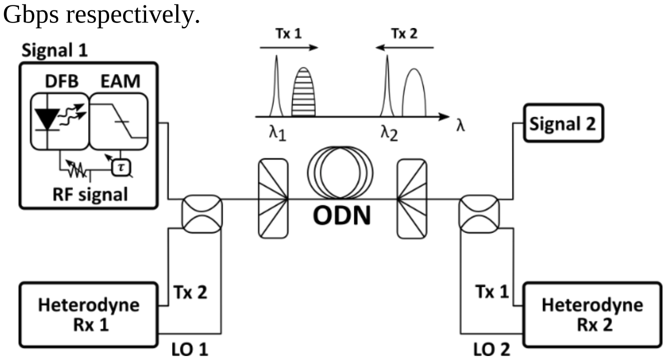


Fig. 2: Proposed network architecture. At the Tx, D-EML in FC-OSSB configuration. At the Rx, heterodyne coherent detection.

II. Operating Principle

As described in [4,5,6], the FC-OSSB modulation can be achieved in a small signal DFB - EAM dual modulation, the DFB providing frequency modulation (FM), and the EAM providing intensity modulation (IM), consecutively. For a given frequency it is obtained when the IM modulation index (m_{IM}) is twice the FM modulation index (m_{FM}). This happens because the field modulation of both sections is then the same in magnitude, and the IM has in-phase 1st harmonics, while the FM has them in counterphase. Then, because consecutive modulations result in the spectral convolution of the FM and IM signals, the 1st harmonic on one sideband is cancelled. This means that the FC-OSSB most important parameters are the amplitude and delay of the modulations at both sections.

For the signal reuse as both Tx and LO, the principle of operation is depicted in Figs. 1, 2 and is as follows. Let us consider a FC-OSSB signal 1, split to act as both Tx1 and LO1, for Rx1, and a signal 2, split into Tx2 and LO2, for Rx2. Both signals are electrically modulated over f_{RF}, and f_{IF} is the the separation in frequency between the respective carriers. The Tx signals travel in opposite directions through a single-fiber link, and reach the opposite terminals. In the example in Fig. 2, LO1 demodulates Tx2, and LO2 demodulates Tx1. Then, the beating between the LO and the Tx signals' carriers is at f_{IF}, unmodulated, and contains both light sources' phase noise information. If the FC-OSSB is performed towards the same sideband for both signals, the beating between the modulation lobe of the received signal and the LO carrier fall in opposite sides of the recovered unmodulated carrier. If both signals use the same frequency f_{RF}, the modulation of Tx 1 falls at f_{IF}-f_{RF}, and the modulation of Tx2 falls at f_{IF}+f_{RF}. Hence, the modulations of the LO and the received signal are spectrally separated at the Rx. Then, as in Fig. 1b), the carrier and the data are retrieved by band-pass filters and mixed, cancelling the phase noise and frequency drifts.

When both signals use the same RF frequency, as the second order beating between both signals' modulations is also at f_{IF}, we see interference over the unmodulated carrier, affecting the PNC operation. This can be mitigated by using lower modulation indexes, as done in the present work, or by using different RF frequencies for upstream (US) and downstream (DS), which will be tested in future works. The corresponding network architecture and transceiver design is shown in Fig 2.

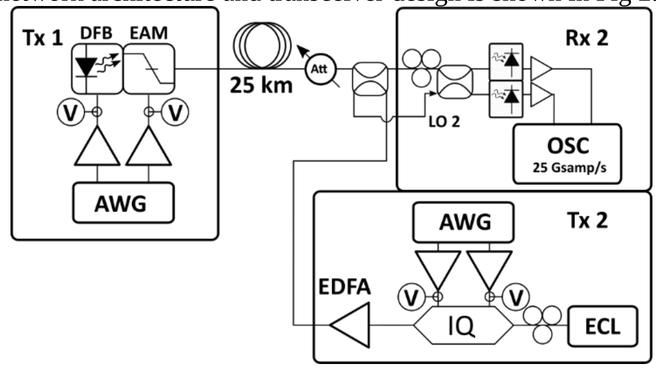


Fig. 3: Experimental set-up used for the technique demonstration.

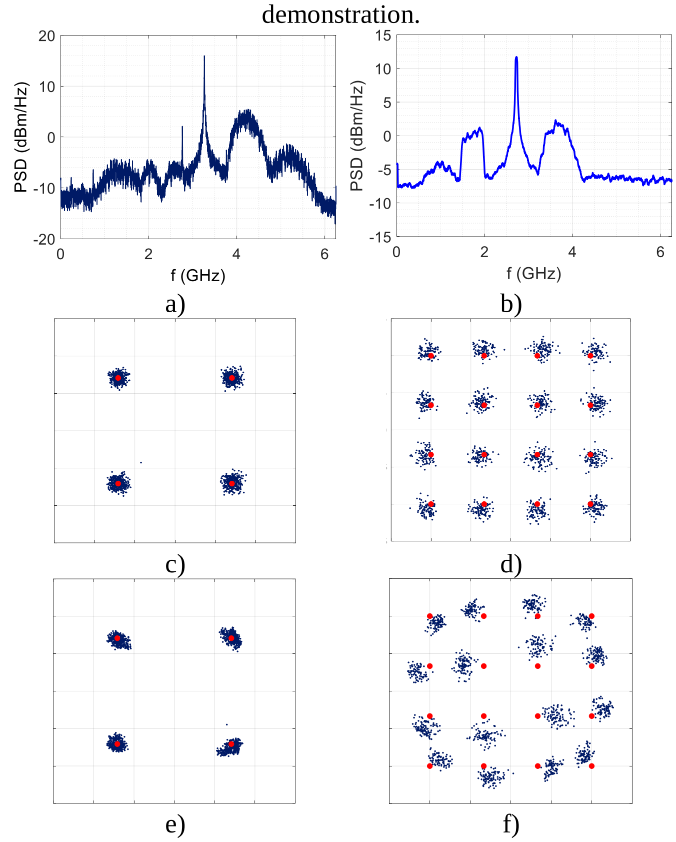


Fig. 4: a) Spectrum of the reaching signal, generated with the D-EML, without LO modulation. **b)** Idem with LO modulation, roll-off 0.1. **c)** constellation of QPSK, m_{IM} of 0.3, unmodulated LO, generated with the D-EML. **d)** idem for 16-QAM. **e)** constellation of QPSK, m_{IM} of 0.7, unmodulated LO. **f)** idem for 16-QAM.

A passive splitter sends copies of the Tx to the optical network and the heterodyne Rx respectively, while also providing the Rx with the received optical signal. The power distribution between the Tx and Rx should be designed as per the specific network requirements. For instance, in networks where minimum power launched to the fiber and modulation extinction ratio are to be met, such as PON standards, more power might be devoted to the Tx. Other scenarios in more application-specific networks might do the opposite to maximize power to the LO and increase Rx sensitivity. In the presented concept demonstration, 3 dB couplers are used as an even compromise. Several options are feasible for the Rx front-end, such as the conventional polarization independent front end [7], polarization scrambling or, most interestingly, the novel 3x3 image-rejection Rx proposed in [8].

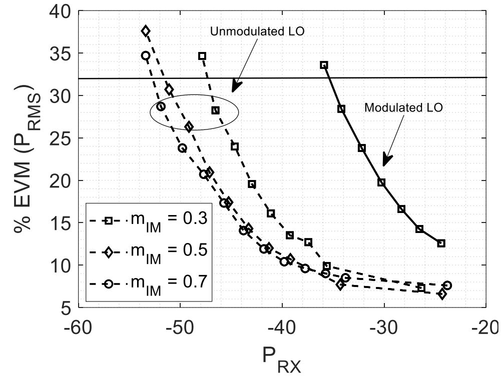
III. Experimental set-up

The experimental set-up can be seen in Fig. 3. The tests use QSPK and 16-QAM RF modulations over 1 GHz electrical carrier and 500 MBaud data bandwidth, provided by an arbitrary waveform generator (AWG). Both use square root raised cosine with a roll-off factor of 1. The detected signal Tx 1 is generated using a TO-CAN distributed feedback laser with a monolithically integrated electroabsorption modulator (EAM), in a D-EML structure, thermally controlled, with linewidth 2.5 MHz. The signal 2 is generated using an external cavity laser (ECL), with linewidth 150 kHz, along with an external IQ modulator, as a 2nd D-EML is not available. An erbium doped fiber amplifier (EDFA) is needed to compensate for the high IQ modulator insertion losses. A 3 dB splitter is used to input Tx 1 from the ODN to the Rx 2, while also splitting the Tx 2 into the 25 km ODN and to the optical front-end as LO2. Thus, both signals travel in opposite directions through 25 km of standard single-mode fiber, introducing Rayleigh backscattering. A variable optical attenuator after the fiber span is used to vary the received power. The states of polarization are manually controlled. The side-band rejection is >15 dB for all OSSB, measured with tone modulations prior to data modulation. This is achieved by controlling the devices biases, amplitude and signal delays as in [4]. With respect to the former study, we have seen that with the better linearity, efficiency and extinction ratio of the EAM used, higher OSSB sideband rejection and signal to carrier ratios can be obtained even for increased m_{IM} of 0.7. This is expected due to higher m_{IM} possible with increased ER, and better correspondence between FM and IM modulations with better linearities. Notably, both the modulation quality and the FC-OSSB sideband ratios of the D-EML are very stable in time, while for the IQ modulator constant adjustment of polarization and biasing is needed.

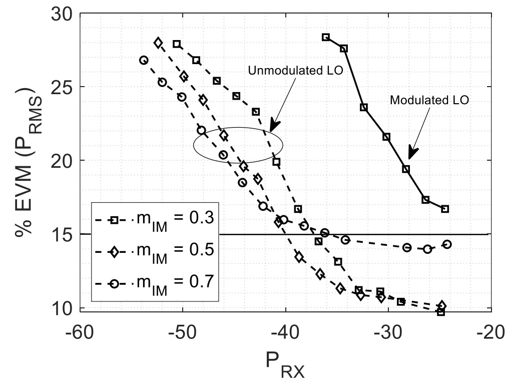
Fig. 4a) and b) show the received signal spectrum with unmodulated LO and after LO modulation, respectively. All measurements use the D-EML as Tx, and the IQ modulator as LO. All error vector magnitude (EVM) measurements use roll-off factor of all signals is 1, but for visualization purposes, in this figure the LO modulation uses roll-off 0.1. Fig. 4c) and d) show QPSK and 16-QAM respectively for m_{IM}=0.3, and e) and f) do the same for m_{IM}=0.7, with unmodulated LO, to check the performance of the D-EML. Good linearity can be observed in c) and d), while m_{IM}=0.7 results in heavily distorted QAM constellations, especially for 16-QAM, as measured in Fig. 4b), due to EAM nonlinearity.

IV. Results

Fig. 5a), b) show the EVM performances for the QPSK and 16-QAM, respectively. In all cases, the D-EML is the Tx and the IQ modulator acts as LO. Dotted lines are the benchmark of the heterodyne PNC technique, and are evaluated for EAM intensity modulation indexes m_{IM} of 0.3, 0.5 and 0.7. They are obtained with a LO power of 0 dBm. Solid lines are the case



a)



b)

Fig. 5: a) EVM with reaching power performance for the 500 MBaud QPSK modulation, for unmodulated LO in dotted lines and in solid for the modulated scenario. **b)** idem for the 16-QAM scenario.

with LO modulation, and are only measured for m_{IM} of 0.3, as higher modulation indexes produce a strong interference from the second order beat between LO and received signal data. The modulated LO signal is only -7 dBm, mostly due to the high loss of our IQ modulator and splitting losses. Real implementations should use high output D-EMLs to achieve LO signals above 0 dBm.

Fig. 5a) shows, for the unmodulated LO, minimum received powers of -52 and -53 dBm for m_{IM} 0.5 and 0.7 respectively, and around -48 dBm for m_{IM} 0.3 in order to obtain EVM below 32%, corresponding to bit error ratio of 10^{-3} [9]. There is almost no penalty between m_{IM} 0.7 and 0.5, while m_{IM} 0.3 has a penalty around 5 dB with respect 0.7 due to lower signal to noise ratio.

With a modulated LO, m_{IM} 0.3 results in -35 dBm of Rx sensitivity, and thus a total penalty of 13 dB with respect the unmodulated case. This is expected, accounting for the LO attenuation, non-ideal sideband rejection and 2nd order beat between data, as well as Rayleigh backscattering over f_{IF}. Being limited by the thermal noise due to the aforementioned low power LO, and considering the 7 dB difference, we can directly estimate that for a LO power of 0 dBm the sensitivity would be about -41 dBm, with a penalty of 6 dB. As commented in section II, having both signals over the same RF frequency resulted in increased interference over the unmodulated carrier as mIM increased. Thus, m_{IM} = 0.5, 0.7 failed to provide tractable detected signals. Future studies will study minimum RF frequency difference to reach quality of service.

Fig. 5b) shows the case of 16-QAM. The threshold EVM to obtain bit error ratio of 10^{-3} is 15%. For the unmodulated LO case, the minimum Rx power is -40 dBm for m_{IM} 0.5, and -37 dBm for m_{IM} 0.3. For m_{IM} 0.7 it can be seen how the non-linear performance of the EAM leads to an EVM floor, so the threshold is reached at -36 dBm. In this case, the modulated LO for m_{IM} 0.3 did not reach the threshold, most likely due to LO attenuation loss, as the slope of the two cases appears to be the, same. Considering the slope of the EVM curves, the modulated LO case with m_{IM} 0.3 has a penalty of around 12 dB with respect the unmodulated scenario, in good agreement with the measured 13 dB in the QPSK measures. Similarly as before, with an increased LO power to 0 dBm we estimate a reduced penalty around 6 dB, and thus a sensitivity of around -32 dBm. There is no symbol equalization or predistortion to account for the EAM non-linear response, which may increase the performance of the higher modulation indexes.

IV. Conclusion

In this work we have proposed and tested the performance of a novel single-laser transceiver with reduced footprint, cost and complexity, for bidirectional links over a single fiber. FC-OSSB with a D-EML at the transmitter is used as the basis of a phase-noise cancelling receiver, with sensitivities with unmodulated LO as low as -53 dBm for QPSK at 1 Gbps and -40 dBm for 16-QAM at 2 Gbps. With a modulated LO in RF FC-OSSB, the sensitivity is -35 dBm for QPSK. We measured penalties of 13 and 12 dB respectively when modulating the LO for QPSK and 16-QAM, respectively. Better performance is expected with higher power LO input. High coherent power budget gains with respect to standard IM-DD RoF systems are thus reported, with phase and frequency noise minimum impact and LO reuse. This work uses TO-CAN packaged EML with no special design adaptation for dual modulation,

Better performance is expected with taylored device design, with larger DFB circuit bandwidth and better optical and electrical isolation between sections, to avoid optical feedback and electrical crosstalk, respectively.

V. References

[1] C. Lim, et al., "Evolution of Radio-Over-Fiber Technology," in Journal of Lightwave Technology, vol. 37, no. 6, pp. 1647-1656, 15 March15, 2019, doi: 10.1109/JLT.2018.2876722.

[2] J. Prat et al., "Technologies for Cost-Effective udWDM-PONs," in Journal of Lightwave Technology, vol. 34, no. 2, pp. 783-791, 15 Jan.15, 2016, doi: 10.1109/JLT.2015.2499381

[3] D. Konstantinou, et al, 5G RAN architecture based on analog radio-over-fiber fronthaul over UDWDM-PON and phased array fed reflector antennas, Optics Communications, Volume 454, 2020, 124464, ISSN 0030-4018, https://doi.org/10.1016/j.optcom.2019.124464

[4] M. Masanas, J. Tabares and J. Prat, "Coherent UD-WDM RoF Fronthaul Network With D-EML Transmitter and Phase-Noise Robust Receiver," in IEEE Photonics Technology Letters, vol. 33, no. 23, pp. 1281-1284, 1 Dec.1, 2021, doi: 10.1109/LPT.2021.3117436.

[5] H. Kim, "EML-based optical single sideband transmitter," *IEEE Photon.Technol. Lett.*, vol. 20, no. 4, pp. 243–245, Feb. 15, 2008, doi:10.1109/LPT.2007.913333.

[6] D. Erasme et al., "The dual-electroabsorption modulated laser, a flexible solution for amplified and dispersion uncompensated networks over standard fiber," J. Lightw. Technol., vol. 32, no. 21, pp. 4068–4078,Nov. 1, 2014, doi: 10.1109/JLT.2014.2346427.

[7] Kazuro Kikuchi, "Fundamentals of Coherent Optical Fiber Communications," J. Lightwave Technol. 34, 157-179 (2016)

[8] J. Tabares and J. Prat, "Low-Complexity Phase-and-Polarization-Diversity Coherent Receiver with High Spectral Efficiency for UDWDM," in Proc. Opt. Fiber Commun. Conf. Exhib., 2021 (OFC), Paper Th5I.2.

[9] Ieee802.org. 2022. EVM tutorial. [online] Available at: <https://ieee802.org/3/cw/public/tf_interim/21_1025/lecheminant_3cw_01_211025.pdf> [Accessed 10 May 2022].