

# Coherent Homodyne TDMA Receiver Based on TO-can EML for 10 Gb/s OOK with <40 ns Guard Interval

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Graceful migration of an IM/DD transmitter towards a single-polarization, analogue coherent burst-mode receiver is experimentally demonstrated for 10 Gb/s on-off keying in TDMA mode, with 400 kHz frame rate and <40 ns guard interval.

## 1. Introduction

Bandwidth-hungry applications in short-reach network segments are expected to grow dramatically in the next years [1], calling for disruptive approaches that can deliver a high capacity in a power-efficient manner. Coherent detection offers the advantage of high spectral efficiency and improved receiver sensitivity, constituting a promising solution to enable scaling of the optical networks. Compared to traditional intensity-modulation direct-detection (IM/DD), coherent systems gain access to more physical dimensions for the purpose of modulation and multiplexing, such as frequency, amplitude, polarization and phase. However, the adoption of coherent technology in short-reach networks is not straight forward; Conventional coherent detection used up to now in long-haul has been based in power-hungry coherent receivers resorting to digital signal processing (DSP) [2]. This prohibits the practical deployment in terms of complexity and energy efficiency in the context of cost-sensitive networks such as found in data centers or access. Low-power DSP-free approaches are needed in these cases, even though analogue solutions may have to draw certain performance-complexity trade-offs such as advanced modulation. DSP-free coherent reception was demonstrated in [3] using envelope detection within a high-speed electronic rectifier. Alternative approaches based on optical or electrical phase-locked-loops have been also demonstrated [4]. However, both schemes necessitate custom electronics which directly impact the cost, size and power consumption.

In this work we aim at an analogue coherent approach that blends in transparently with low-complexity modulation. We experimentally demonstrate homodyne detection of 10 Gb/s on-off keying in TDMA at short guard interval of <40 ns. We show that this coherent receiver can be as simple as an externally modulated laser (EML), which all-optically synchronizes to free-running optical transmitters with a locking speed in the nanosecond range.

## 2. Analogue Coherent Homodyne Reception for Filterless Optical Ultra-Dense WDM Networks

High spectral occupancy, efficient use of resources and higher optical budgets for optical networks can be guaranteed through a coherent ultra-dense WDM approach with TDMA reception for each of the sub-wavelengths. Figure 1 presents such a scheme that is based on free-running transmitters (TX) and a time-shared coherent receiver (CRX). An EML is employed for either purpose. While its function as transmitter is well known, the use of an EML as coherent detector can be beneficial as it allows homodyne reception of a data signal, thus providing an analogue CRX solution [5]. To provide CRX functionally through an EML, its DFB section serves as injection-locked local oscillator (LO), while its EAM as the photodiode is slightly biased at absorption. The prerequisite for establishing a coherent sub-wavelength  $\lambda_i$  is a spectral allocation of the transmitted optical frequencies  $\nu^{(1)}, \nu^{(2)}$  within the vicinity of the LO at  $\nu^*$  of the receiving EML, and in particular within its locking range LR. The locking range depends on the injection level  $P_{RX}$  and is typically in the range of 100 MHz to 1 GHz, as will be characterized shortly. The EML-based transceiver approach ensures a cost-effective ultra-dense WDM implementation. Although a similar coherent TDMA approach has been demonstrated earlier in the field of radio-over-fiber transmission [6], this work aims at analogue baseband modulation with a low inter-burst guard interval  $\tau_G$ .

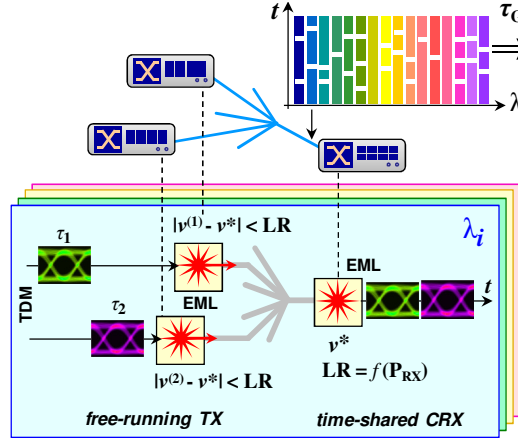


Fig. 1. Ultra-dense WDM in TDMA with low-complexity coherent receiver.

### 3. Experimental Setup and Receiver Locking

The experimental setup is shown in Fig. 2a. Two transmitters ( $TX_{1,2}$ ) are sharing a CRX in TDMA mode. Transistor-outline EMLs with a bandwidth of 7.3 GHz and an integrated micro-cooler have been chosen for several opto-electronic conversion functions. Although all three EMLs are nominally operating at 1548.51 nm, their exact optical emission frequency  $\nu^{(1)}, \nu^{(2)}$  will generally differ due to the free-running laser emission. Burst-mode on-off keying at 10 Gb/s has been chosen for data transmission at a TDMA frame rate of 400 kHz. The TDMA frame is shown in Fig. 2b at point  $O$  of the setup. The guard interval  $\tau_G$  between the bursts is  $< 100$  ns, and in particular 37 ns at the transition from  $\nu^{(2)}$  to  $\nu^{(1)}$  ( $\Xi$ ). In order to allow for passive branching of the two burst signals with a simple 50/50 coupler, gated semiconductor optical amplifiers (SOA) at the transmitter outputs ensure a high signal extinction before and after the data burst and a signal launch of 6 dBm at the transmitter output. The LO of the CRX, which is characterized through its free-running frequency  $\nu^*$ , is injection-locked to the incident signal at  $\nu^{(1)}, \nu^{(2)}$ . A low-noise amplifier (LNA) is used as electrical front-end since a TIA cannot be externally co-integrated with a TO-can EML. Polarization-diversity is supported by a tandem-EML configuration [7], which was omitted in the present work due to unavailability of a fourth EML device. Manual polarization control (PC) is therefore applied.

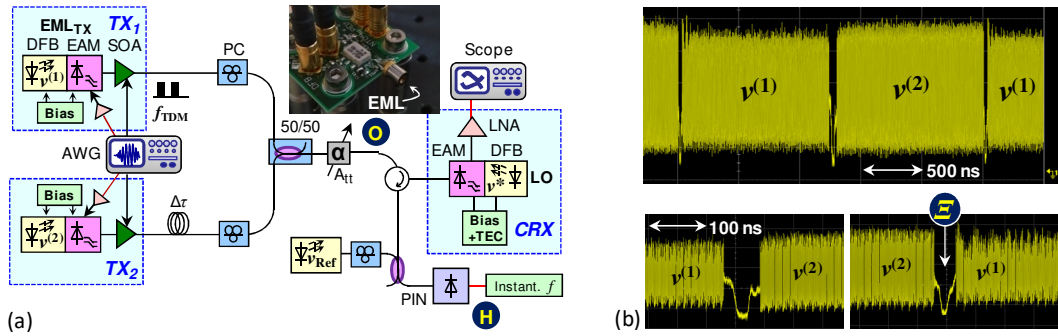


Fig. 2. (a) Experimental setup for evaluating coherent reception in TDMA and (b) transmitted TDMA frame as delivered to the CRX.

The static locking range of an employed EML is presented in Fig. 3a for an EAM section that is biased for the purpose of signal reception. The locking range remains above 100 MHz for a low injection power of -30 dBm, meaning that the LO of the CRX can deviate by  $\pm 50$  MHz from the incident data signal to ensure receiver locking. For higher injection, values of more than 1 GHz can be easily obtained.

The dynamic locking process for TDMA reception has been characterized through heterodyning the CRX emission with a stable reference laser  $\nu_{Ref}$  (point H in Fig. 2a). Figure 4 reports the spectra for four cases: the free-running CRX emission without injection (I), the reception of one TDM channel (II, III) and the entire TDMA frame (IV), each of them at an injected level of -10 dBm. When an optical burst is received by the CRX, the intermediate

frequency (IF) shifts due to the optical injection. A sharp spectral line appears, which is determined by the transmitted emission frequency at  $\nu^{(i)}$ . For injection at both TDM channels the IF beat note vanishes due to the small guard interval between the two transmitter bursts, which leads to a diminished duty cycle at which the free-running LO  $\nu^*$  beats the reference. The transition between two TDM bursts is resolved in Fig. 3b in terms of instantaneous beat frequency after digital acquisition of the TDMA frame. These two instantaneous deviations of 450 and -570 MHz from the beat note of the LO ( $\nu^*$ ) follow the burst envelopes of the injected TDM channels as shown in Fig. 2b. The slightly longer transition from  $\nu^{(1)}$  to  $\nu^{(2)}$  with free-running LO gap between the packets ( $\alpha$ ) can be also noticed. Given the resolution that can be achieved through the digital estimation, a locking time of  $<10$  ns can be anticipated for the CRX, which is supported by earlier studies [8].

Finally, the long-term drift of the transceivers has been investigated by beating two detuned EMLs. Figure 3c presents the time evolution of the frequency excursion  $\delta IF$  from the resulting IF. We experienced a fast drift with a peak-to-peak deviation of less than 87 MHz, and a long-term drift with an excursion of 240 MHz within two hours. There are no fast fluctuations that would exceed the locking range, which is a prerequisite for stable CRX locking.

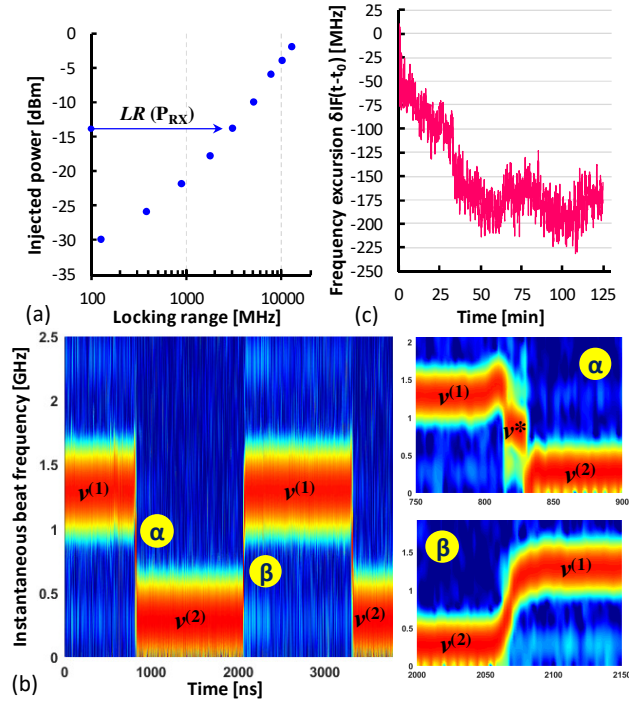


Fig. 3. (a) Locking range of EML. (b) Instantaneous IF for TDM injection in CRX. (c) Beat frequency drift when beating two EMLs.

#### 4. Coherent Reception in TDMA

The reception sensitivity was evaluated as function of the optical loss budget between transmitters and receiver, for which a variable attenuator ( $A_{it}$ ) has been included before the receiver (Fig. 2a). Since no burst-mode BER tester was available, the BER was estimated through off-line processing by performing decision sampling with adaptive amplitude threshold and subsequent error counting. Figure 5a presents the BER performance for the signals deriving from both transmitters for reception in continuous ( $\bullet, \blacktriangle$ ) and TDMA ( $\circ, \triangle$ ) mode.

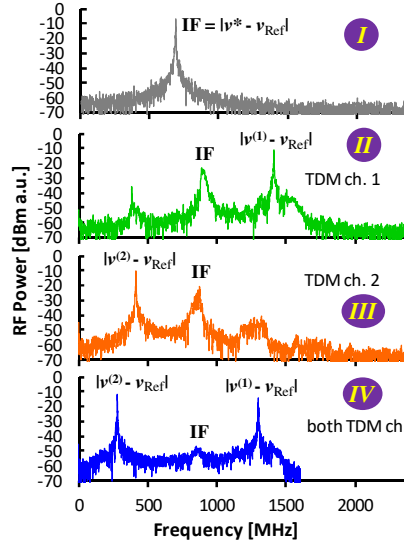


Fig. 4. Beat spectra for TDMA locking of CRX.

An optical budget of 24.8 dB is supported at the hard-decision FEC limit of  $3.8 \times 10^{-3}$ . This budget is subject to improvement when co-integrating the EML detector with a TIA-based electrical front-end. For a reduced loss budget, meaning a higher received power, undesired direct-detection terms and increased suppression of low-frequency components due to injection locking lead to a degradation in the achieved BER. This leads to a dynamic range of  $\sim 8$  dB at the FEC limit. The optimal loss budget, for which a BER in the  $10^{-5}$  range can be obtained, is 19.5 dB. Corresponding eye diagrams are presented in Fig. 5b for signal reception in continuous (C) and TDMA (T) mode. The eyes indicate a suppression of low-frequency components, as it applies for the aforementioned injection locking. Nevertheless, the results prove that this enabling concept for homodyne detection is compatible with the reception of baseband modulated broadband signals. If the compatible loss budget of 24.8 dB is eroded by passive power splitting, a total split of 1:128 is supported between transmitters and receivers. The extensive branching can be conveniently used to establish a massive number of ultra-dense WDM channels.

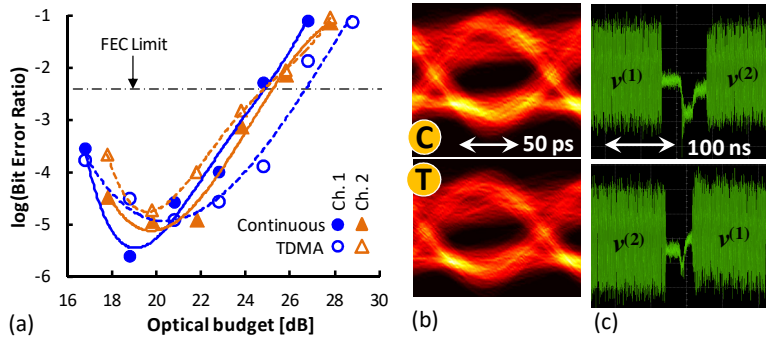


Fig. 5. (a) BER performance for both transmitters in continuous (C) and TDMA (T) mode and (b) corresponding eye diagrams. (c) Transitions of burst signals after coherent reception.

## 5. Conclusions

We have experimentally demonstrated single-polarization, coherent signal reception of 10 Gb/s OOK in TDMA using no more than an EML. Fast injection locking enables homodyne detection of data bursts at short ( $< 40$  ns) guard interval. The compatible optical budget of  $\sim 25$  dB, which is obtained even without TIA front-end, allows to collapse a high number of ultra-dense WDM sub-wavelengths over a filterless, high-split distribution network. Moreover, the fast locking of the receiver supports short-lived data flows as they apply in datacenter infrastructures.

## 6. Acknowledgement

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## 7. References

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