Two-Fiber Self-Homodyne Transmission for Short-Reach Coherent Optical Communications

# Two-Fiber Self-Homodyne Transmission for Short-Reach Coherent Optical Communications

**G. Rizzelli[1], A. Nespola[2], S. Straullu[2], F. Forghieri[3], R. Gaudino[1]**
*[1]Politecnico di Torino, PhotoNext Center, Corso Duca degli Abruzzi 24, Torino, Italy*
*[2]LINKS Foundation, Via Pier Carlo Boggio, 61, Torino, Italy*
*[3]Cisco Photonics Italy S.r.l., 20871 Vimercate, Italy*
*Tel: (0039) 011 0904092, e-mail: giuseppe.rizzelli@polito.it*

**ABSTRACT**
We experimentally evaluate the performance of two-fiber self-homodyne short-reach transmission, showing that it enables the use of DFB laser provided that the optical path mismatch is kept below 1 m for PM-QPSK and 0.5 m for PM-16QAM.
**Keywords**: Fiber optic communications, coherent detection, self-homodyne, DFB lasers, phase noise.

## 1. INTRODUCTION

Emerging technologies such as artificial intelligence, virtual and augmented reality, Internet of Things, cloud services and autonomous cars are driving the generation of massive amounts of data on the communication network from the core to the access and data center level.

During the last decade, long-haul optical networks have witnessed a capacity advance to multi-Terabit over thousands of kilometers with the advent of coherent detection (CD), which have progressively replaced traditional systems based on intensity modulation and direct detection (IM-DD). Nowadays, short-reach networks (<10 km) are also facing the challenge to upgrade their capacity per wavelength beyond 100 Gb/s/λ to support the growing traffic demand, and industry organizations such as the Optical Internetworking Forum (OIF) and the IEEE have initiated CD standardization activities [1], reinforcing the view of optical communication moving to shorter reach, high volume applications.

To date, two main complementary factors have prevented CD from being extensively employed in short reach: cost and complexity [2]. Considering that a great part of the cost for an integrated transceiver is related to the laser, recently, Morsy-Osman et al. [3] proposed a CD solution for intra-datacenter (IDC) high-speed communication without digital signal processing (DSP) and without local oscillator (LO) laser, showing that it can greatly reduce power consumption and transceiver complexity. In the proposed two-fiber self-homodyne system, as schematically shown in Fig. 1a, the transmitted signal is split prior to modulation and the CW portion is sent on one fiber, whereas the modulated portion propagates along another fiber inside the same cable. At the CD receiver, the CW signal is used as LO. The proposal is interesting for IDC, for instance in scenarios using multi-parallel optic (MPO) cable and where the "waste" of one fiber for the LO could be accepted compared to a traditional IM-DD solution when considering the increase in bit rate enabled by CD.

In this paper, we extend the analysis of [2] and [3] by focusing on its capability of using lower cost lasers. In particular, we experimentally investigate on the use of DFB lasers as a low-cost alternative to narrow linewidth external cavity lasers (ECL), the most commonly used for CD. As a main result of our paper, we show that the two-fiber self-homodyne approach enables the use of DFB lasers provided that the path difference between the two fibers is below 0.5 meter for PM-16QAM.

The paper is organized as follows. We first characterize the linewidths of commercial DFB and ECL lasers through the coherent delayed self-heterodyne (CDSH) method [4] for very short optical path differences in the range of a few meters, to confirm that if the optical path mismatch is shorter than the coherence length of the laser, the resulting self-beating linewidth decreases. Then we measure the performance of a self-coherent system in back-to-back (B2B) and with 2.5 km link as a function of the path difference, showing a 1 dB sensitivity penalty at about 2 m and 0.5 m path difference for polarization multiplexed- (PM-) QPSK and PM-16QAM modulation respectively, at BER=$2\cdot10^{-2}$. We conclude by discussing on resulting power budget and possible architectures.

## 2. DFB LINEWIDTH CHARACTERIZATION

In order to obtain laser linewidth measurements, we experimentally implemented the well-known coherent delayed self-heterodyne (CDSH) method according to the schematic proposed in [4], where the laser signal is split in two branches, then one of the two is frequency shifted (by $f_{AOM}$=27 MHz) using an acousto-optic modulator (AOM), while the other is delayed by a fiber with length L+ΔL, where L is the length of the other fiber. The two signals coming from the two paths are combined again in a photodiode. We focused on the CDSH

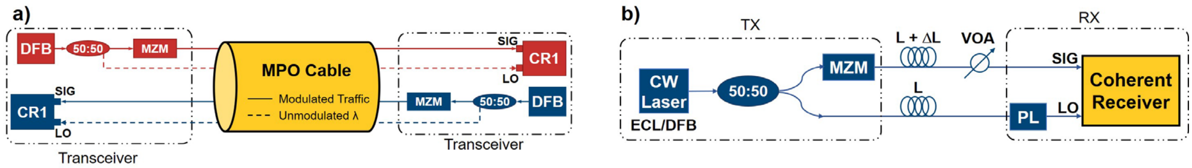


*Figure 1. a) Block diagram of the proposed architecture and b) experimental setup of the self-coherent transmission system. DFB: Distributed Feedback Laser; CR: Coherent Receiver; MPO: Multi Parallel Optics; MZM: Mach Zhender Modulator; ECL: External Cavity Laser; VOA: Variable Optical Attenuator; SIG: Signal; LO: Local Oscillator, PL: Polarization Locker.*

approach since the resulting beating linewidth for a given path length difference will be exactly the same of the two-fiber CD system shown in Fig. 1b and investigated in the following Section.

The linewidth measurements were performed on 1550 nm commercial lasers (an ECL and a DFB whose specsheets indicate, respectively, a <100 kHz and <10 MHz nominal linewidth) for ΔL ranging from 0 m to 5 m. Accurate estimation of the path difference was obtained by sending a 0.1 ns pulse on the two arms and measuring the time delay between the two at the input of the CR by means of a PIN photodector and an oscilloscope.

The beat-signal (that in the electrical spectrum is placed around $f_{AOM}$), was acquired through a real-time oscilloscope, then the resulting spectrum was estimated via FFT. Fig. 2a and Fig. 2b show the normalized power spectral density with 50 kHz resolution bandwidth (RBW) of an ECL and a DFB laser for different path differences ΔL. As expected, the ECL beating spectrum remains unaltered for all the considered values of ΔL, since the path mismatches are much shorter than its coherence length (about 2.1 km for a 100 kHz linewidth). On the contrary, the DFB self-beating linewidth (SBL) strongly decreases for decreasing ΔL, as shown even more evidently in Fig. 2c where a 500 kHz RBW was used. This anticipates that the phase noise penalty that affects CD systems when using DFB could be reduced by decreasing ΔL, as we will confirm in the transmission experiments in the next Section 3. Intuitively, the linewidth (or phase noise) reduction for decreasing ΔL can be easily interpreted at the limit of ΔL=0. In this case, independently on the instantaneous value assumed by phase noise, the two signals reaching the photodiode (or the coherent receiver in the following Section 3) have exactly the same phase, so the resulting beating is always perfectly in phase.

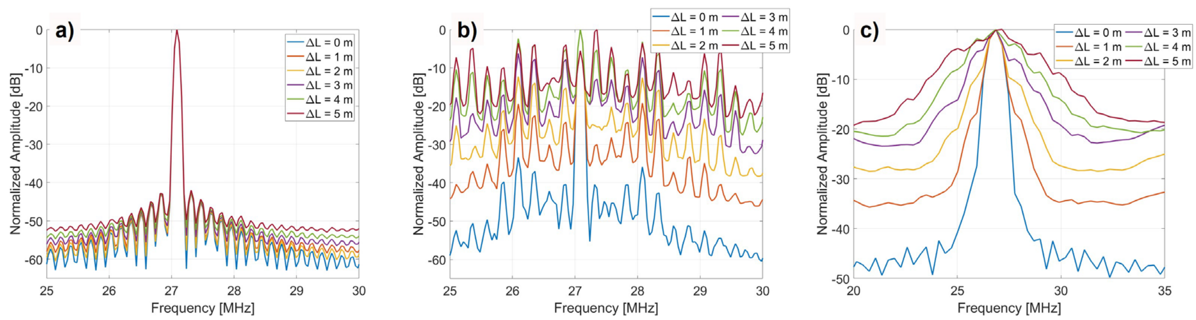


*Figure 2. Measured power spectral density of a) an ECL laser with 50 kHz RBW, b) a DFB laser with 50 kHz RBW and c) a DFB laser with 500 kHz RBW for different path differences ΔL.*

## 3. EXPERIMENTAL SETUP AND RESULTS

The self-coherent setup used in our experiments (Fig. 1a) is very similar to the CDSH setup, except that the AOM is replaced by an external Mach-Zhender modulator (MZM) to generate PM-QPSK or PM-16QAM signals. We drive the MZM by a 92 GS/s arbitrary waveform generator (AWG) working as a four-output digital-to-analog converter, using off-line processing approach. The input digital streams are four independent PRBS15 sequences. After fiber transmission and attenuation, we used a commercial CD receiver (CR) and a real time oscilloscope at 200 GS/s and post-processed the data after downsampling at two samples per symbol through typical off-line DSP routines for CD systems. We characterize the system performance measuring BER vs. received optical power $P_{RX}$, varied at the CR input through a variable optical attenuator (VOA).

Fig. 3a shows the B2B sensitivity curves for the DFB-based system with 28 GBaud PM-QPSK modulation and for ΔL values from 0 m to 5 m, with 1 m step. As anticipated, the effects of phase noise induce a power penalty that increases with ΔL. Moreover, for ΔL=0 m, we measured that the DFB setup has no penalty compared to an ECL setup, showing that the DFB laser behaves exactly as the ECL laser in a self-coherent setup with small ΔL.

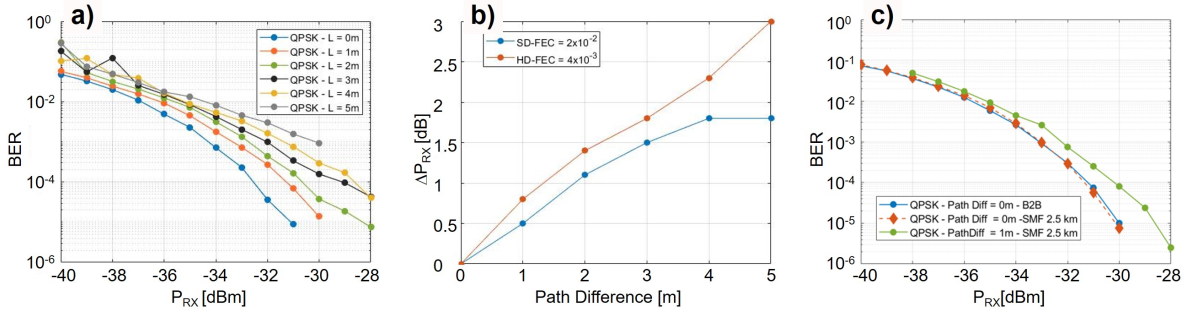


*Figure 3. a) B2B sensitivity curves for the DFB-based system with 28 GBaud PM-QPSK modulation and for ΔL values from 0 m to 5 m. b) Received optical power penalty for SD-FEC BER threshold $2{\cdot}10^{-2}$ and HD-FEC BER threshold $4{\cdot}10^{-3}$. c) Comparison of sensitivity curves in B2B and with a 2.5 km SMF link for 0 m and 1 m path difference using DFB laser.*

Fig. 3b shows the evolution of the penalty vs. ΔL at two different BER levels: a $2{\cdot}10^{-2}$ soft-decision forward error correction (SD-FEC) threshold, and a $4{\cdot}10^{-3}$ hard-decision (HD) FEC threshold. In both cases, the figure shows that the path difference should remain below 1 meter to have less than 1 dB penalty. The following Fig. 3c shows the sensitivity curves for the same system when a 2.5 km SMF link was included and for 0 m and 1 m path difference. In this case, the correct SOP of the LO is ensured by a polarization locker (PL), similarly to what it was proposed in [2] and [3], and implemented experimentally in [5] with a Silicon Photonic integrated device. Please note that this set of measurements was carried out at a different time than those presented in Fig. 3a, therefore a non-perfect modulator bias point or other impairments may have affected the B2B sensitivity. Nevertheless, it is worth noting that even in a realistic transmission scenario 0 m path difference is perfectly equivalent to B2B transmission, and that when ΔL =1 m the power penalty is again 0.5 dB at the SD-FEC threshold and 0.75 dB at the HD-FEC threshold, as in Fig. 3b.

In Fig. 4 we show the same type of results, but for the 28 GBaud PM-16QAM modulation format. The path difference that ensures less than 1 dB penalty is reduced to approximately 0.5 meter. Also in this case no significant difference was observed in realistic transmission over a 2.5 km link (see Fig. 4c).

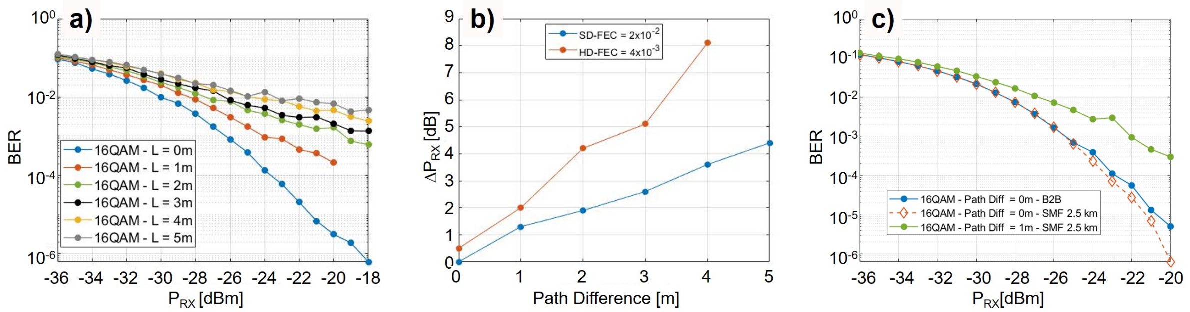


*Figure 4. a) B2B sensitivity curves for the DFB-based system with 28 GBaud PM-16QAM modulation and for ΔL values from 0 m to 5 m. b) Received optical power penalty for SD-FEC BER threshold $2{\cdot}10^{-2}$ and HD-FEC BER threshold $4{\cdot}10^{-3}$. c) Comparison of sensitivity curves in B2B and with a 2.5 km SMF link for 0 m and 1 m path difference using DFB laser.*

## 4. COMMENTS AND CONCLUSION

We have experimentally evaluated the effect of the laser linewidth increase with the path difference in a self-coherent transmission system for IDC applications. We showed that when 28 GBaud PM-QPSK and PM-16QAM modulation formats are used the phase noise-induced sensitivity penalty reaches 1 dB when the path difference between the signal and the LO is 1.8 m and 0.8 m respectively at the SD-FEC threshold. We also found that the penalty is equivalent in B2B and for transmission over a 2.5 km SMF fiber. Our results prove that the use of DFB lasers in the proposed system is possible, even for PM-16QAM up to fiber path difference of less than about 0.5 meters, a requirement that seems not critical for instance in multi-parallel optic cables, where the two fiber would have almost identical length, since they would run in the same MPO.

We now discuss the resulting power budget and the consequent possible system architectures. We do not consider any optical amplifier, as it is typical for IDC. For PM-16QAM, the sensitivity at SD-FEC BER=$2{\cdot}10^{-2}$ is around -32 dBm (Fig. 4a), whereas the average power at the output of the modulator was in our experiments -6 dBm (considering that we have been using commercial components and including the TX 1x2 splitter loss which we can conservatively set to 4 dB). Thus, we can reasonably estimate a very promising available power budget equal to 26 dB, that allows to envision extension of the proposed architecture to CWDM, since there is ample margin to cope with the additional loss of the required CWDM mux-demux filter, or even more exotic implementations in which in a 10-fiber MPO (5 fibers for each direction), a 1x5 splitter is used at the transmitter, then 4 outputs are modulated, and the remaining one acts as a common local oscillator for 4 coherent receivers, thus reducing the impact of dedicating one fiber to the LO.

**ACKNOWLEDGEMENTS**

The authors thank the PhotoNext Center at Politecnico di Torino, where the experiments were performed.

**REFERENCES**

[1] The Optical Internetworking Forum, “Flex Coherent DWDM Transmission Framework Document,” (2017) [Online].

[2] J. K. Perin, A. Shastri and J. M. Kahn, “DSP-free coherent-lite transceiver for next generation single wave-length optical intra-datacenter interconnects,” Opt. Express26, 8890-8903 (2018).

[3] M. Morsy-Osman, M. Sowailem, E. El-Fiky, T. Goodwill, T. Hoang, S. Lessard and D. V. Plant, “Design ofLow-Power DSP-Free Coherent Receivers for Data Center Links,” IEEE J. Lightwave Technol.35, 4650-4662 (2017).

[4] K. Kikuchi and K. Igarashi, “Characterization of Semiconductor-Laser Phase Noise with Digital Coherent Receivers,” inOptical Fiber Communication Conference/National Fiber Optic Engineers Conference, OSATechnical Digest (CD) (Optical Society of America, 2011), paper OML3.

[5] A. Nespola et al., “Proof of Concept of Polarization-Multiplexed PAM Using a Compact Si-Ph Device,” IEEE Photonic Tech. L.31, 62-65 (2019).