IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 7, Number 5, October 2015

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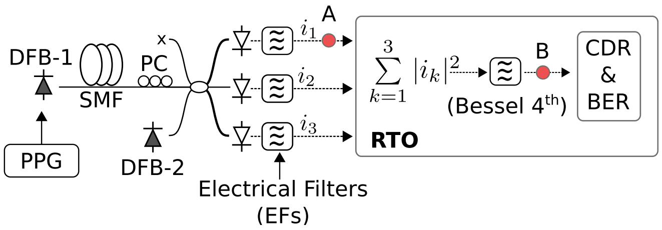

DOI: 10.1109/JPHOT.2015.2486678

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DOI: 10.1109/JPHOT.2015.2486678

Manuscript received September 3, 2015; accepted September 27, 2015. Date of publication October 5, 2015; date of current version October 20, 2015. This work was supported in part by the EU FP7 Project COCONUT under Grant Agreement 318515 and in part by the Italian project PRIN ROAD-NGN funded by MIUR. Corresponding author: R. Corsini (e-mail: rcorsini@opiphotonics.com).

Abstract: We demonstrate 10-Gb/s transmission over more than 130 km of G.652 fiber using a simple directly modulated distributed feedback (DFB) laser and a new "chirp-managed" approach based on a low-complexity coherent receiver. The "chirp-managed" effect, which has been obtained in the past by optical spectral reshaping, is conveniently achieved here by means of simple electrical filtering of the received signal at the intermediate frequency. Due to coherent detection, the receiver sensitivity was -38 dBm at bit error rate (BER) $= 1.8 \times 10^{-3}$. No colored filters and no dispersion compensation (optical or digital signal processing (DSP)-based) were used at the receiver side. We show that the coherent system presented here, based on off-the-shelf components, is robust against variations of DFB chirp, local oscillator detuning, and electrical filter bandwidth over ranges wide enough to guarantee a simple and cost-effective implementation for 10-Gb/s long-reach passive optical network applications.

Index Terms: Coherent communications, fiber optics and optical communications, optical communications.

1. Introduction

With the advent of fifth-generation (5G) mobile technology, next generation optical access networks are expected to support services with bandwidth much larger than today. Fueled by the exponential growth of video services distributed ubiquitously on fixed and mobile terminals, huge amounts of traffic will have to be transported in the access segment of the network. The big challenge Telco Operators and system providers have to face in this scenario is to cost effectively scale their access networks to meet the expected capacity increase. To achieve this, re-use of existing Optical Distribution Networks (ODNs) is mandatory, although legacy Passive Optical Network (PONs) equipment transporting current access traffic is already in service on them. In order to support the future bandwidth growth over existing ODNs, the ITU-T and the IEEE in collaboration with the Full Services Access Network (FSAN) group, have defined their respective 10 Gb/s PON solutions, namely ITU-T XG-PON (Recs. G.987) and IEEE Std. 802.3 av 10GE-PON. Moreover, a 40 Gb/s capable PON architecture based on wavelength stacking of four XG-PONs (NG-PON2) is currently under standardization by ITU-T in the series of Recs. G.989.

At the same time, long-reach passive optical network (LR-PON) are also of interest. Indeed, LR-PONs are attractive because they enable network operators and service providers to reach a vast number of users and simultaneously consolidate their networks by reducing the number of local exchanges with a consequent simplification of network management and reduction of operating expenses [1], [2]. Network consolidation issues have already entered current ITU-T standards with the introduction of the so-called Reach Extenders (G.984.6, G.987.4), which are devices capable of guaranteeing PON operation over a distance up to 60 km. However LR-PONs with reach exceeding 100 km are still outside the scope of current standards. A 10 Gbit/s LR-PON with such a reach needs dispersion compensation and external modulation to overcome the chromatic dispersion of common single mode fibers (G.652) and optical amplification in order to overcome the losses (including those due to the high splitting ratio) of the ODN [3].

In recent years, much interest has grown in applying coherent detection and digital signal processing (DSP) in the access segment to extend the system reach and to support high user density [4]. Yet, present-day coherent receiver technology, with all the appealing features offered by high-speed A/D converters and advanced DSP techniques, which have been so advantageous and successful for transport networks, is hardly suitable (nor even required in its full capability) for access networks, where receivers are expected to be low-cost, simple, and robust [5].

Recently, we demonstrated a cost-effective coherent envelope detection scheme enabling the use of directly modulated (DM) lasers with adiabatic chirp in Wavelength Division Multiplexed (WDM) PON access networks at 1.25 or 2.5 Gb/s per channel [6]. A 120° hybrid consisting of a commercial 3×3 fused fiber coupler was used in the coherent receiver to implement phase diversity, and commercial low cost DFBs were used as transmitter and local oscillator (LO) lasers. The obtained sensitivities (measured at FEC level) were −50 and -47 dBm for 1.25 Gbit/s and 2.5 Gbit/s modulation, respectively. In the proposed scheme, the Optical Network Unit (ONU) is kept at a low-complexity level and colorless (i.e. built without wavelength dependent optical components). In [7] we also exploited the narrow optical bandwidth of coherent receivers to realize very sharp filtering ($<$ 10 GHz), which is difficult to obtain in the optical domain.

In this paper, we show that the approach of [7] can also be extended to 10 Gbit/s DM-DFB lasers exhibiting a prevalent adiabatic chirp. In particular we experimentally demonstrate, for the first time to the best of our knowledge, that an effect similar to chirp management [8] can be obtained by using a coherent homodyne receiver with proper post-detection filtering: this is equivalent to the optical filtering at the transmitter side implemented in [8]. Thanks to this coherent chirp-managed (CM) approach, 10 Gbit/s ASK transmission over 131 km G.652 of fiber is achieved using a DM-DFB laser as a transmitter and a homodyne coherent receiver, without optical amplification (Erbium-Doped Fiber Amplifier, EDFA) and dispersion compensation (optical or DSP based). The measured pre-Forward Error Correction (FEC) sensitivity of the CM coherent receiver is -38.2 dBm.

Thanks to these features, the proposed technique offers an interesting solution for the realization of a 10 Gbit/s LR-PON where the use of expensive components such as external modulators, etalons, optical amplifiers, dispersion compensation modules, is not desirable. Finally, the proposed approach can also be useful for coherent receivers based on DSP, because it reduces DSP complexity by eliminating the need of chromatic dispersion compensation/estimation [9].

2. Approach Description

In order to explain our approach, it is useful to recall that the well-known CM approach [8] exploits the chirp of a direct modulated laser to overcome the chromatic dispersion of optical fibers. The scheme of the CM approach as presented in [8] is shown in Fig. 1(a). The output of a strongly biased directly modulated DFB is passed through the transmission edge of a Fabry–Pérot optical filter which acts as an Optical Spectral Reshaper (OSR). The function of the OSR is twofold: first, it increases the Extinction Ratio (ER) of the optical bit stream by passing the “1” (mark) bits, blue shifted with respect to the “0” (space) bits due to the chirp, and suppressing the “0”s (FM/AM conversion in the figure); secondly, it generates a phase rule by which “1” bits separated by an odd

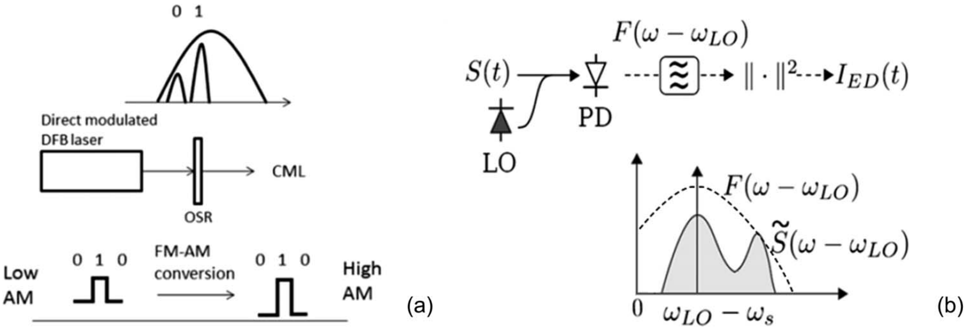

Fig. 1. (a) Schematic of the classical CM Laser approach (OSR, Optical Spectral Reshaper; AM, amplitude modulation; FM, frequency modulation) [8]. (b) CM approach based on coherent receiver and appropriate electrical filtering of the Intermediate Frequency (IF) signal (where $F(\omega)$ is the transfer function of the filter, $S(t)$ and $\tilde{S}(\omega)$ are the optical signal and the optical signal spectrum respectively, and $I_{ED}(t)$ is the demodulated current).

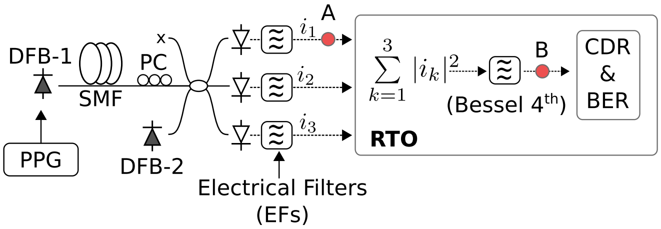

Fig. 2. Schematic of the experimental set-up: PPG, pattern generator; PC, polarization controller; SMF, single mode fiber; RTO, real time oscilloscope; LPF, low-pass filter; CDR, clock and data recovery; BER, bit error ratio.

number of “0” bits are π out of phase. It is this phase rule that increases dispersion tolerance: two broadened “1” bits before and after a “0” bit spill out their energy into the “0” time slot and interfere destructively because they are out of phase. In order to obtain this effect, the chirp (frequency deviation) between the “1” and “0” symbols must be half the bit rate (e.g. 5 GHz for 10 Gbit/s, as in the case of minimum shift keying, MSK) [8].

In our system, we implement the function of the OSR in the coherent receiver after the optical-electrical conversion by applying a suitable electrical filtering at the intermediate frequency (IF). This filter performs a spectral shaping in the electrical domain equivalent to that operated by the OSR in the optical domain. Therefore, we obtain a CM approach without applying an optical filter, as shown in Fig. 1(b). Doing so also avoids the rather high losses of the OSR (8–10 dB) [8]. Clearly, filtering and fiber dispersion are commuting linear operations, therefore applying filtering before or after dispersion has acted is irrelevant. In addition, since the coherent detection is also a linear process, the filtering can be applied after the down-conversion process. We also point out that this approach is not dependent on the particular implementation of the optical front-end of the coherent receiver.

The advantage of the proposed solution is the simplicity of the transmitter: a simple DFB laser directly modulated without any filter and locking system, thus coupling most of his output power into the transmission fiber. The same advantages apply when our solution is compared to solutions based on an external modulator; in addition no dispersion compensation element is required. Finally we note that this solution remains useful also in the case of a digital coherent receiver using DSP, because a simplified DSP stage can be used without the chromatic dispersion compensation algorithm based on a time or frequency domain equalizer [9], [10].

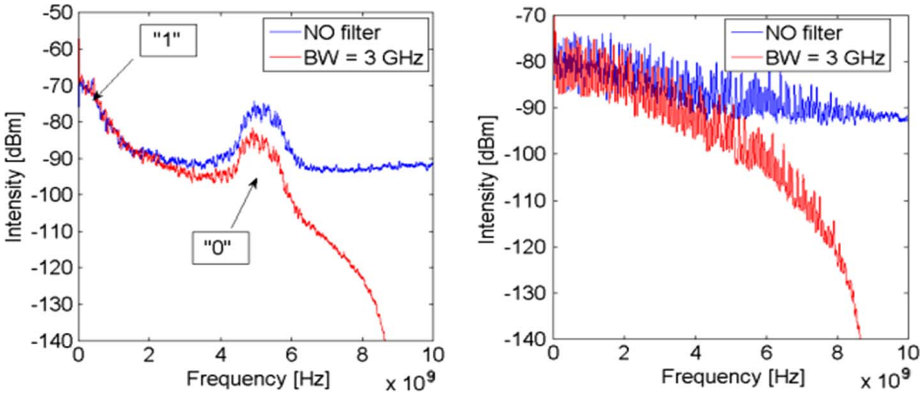

Fig. 3. Electrical spectra of DFB-1 as measured at point A of Fig. 2 for (left) 1 Gbit/s modulation and (right) 10 Gbit/s modulation. Blue curve: full bandwidth; red curve: after 3 GHz electrical filtering.

3. Experimental Set-Up

The schematic of the experimental setup used to demonstrate our approach is shown in Fig. 2. The transmitter was a DFB laser (DFB-1) directly modulated at 10 Gbit/s by a non-return-to-zero (NRZ) pseudorandom bit sequence $(2^7 - 1)$ to produce an ASK signal. Laser emission wavelength and laser line-width were 1540.55 nm and about 10 MHz respectively. The power of the optical signal at the output of the DM-DFB-1 was 1.8 dBm at 50 mA driving current. Spools of G.652 fiber $(D = 16 \text{ ps/nm/km}, \alpha = 0.2 \text{ dB/km})$ of different lengths were combined to obtain transmission lines up to 131 km. A phase diversity coherent receiver based on a 3×3 symmetrical fused-fiber optical coupler (120° hybrid) was used as an envelope detector [11]. A second DFB laser (DFB-2) acted as a local oscillator (LO). DFB-2 (linewidth 6 MHz) was operated free-running without any frequency control system. Homodyne operation was achieved by tuning DFB-2 close to the frequency of DFB-1. Tuning was done by changing the laser operating temperature (coarse tuning) and bias current (fine tuning).

The signal and the LO were mixed by a 3×3 symmetrical coupler; then the three outputs of the coupler were sent to three nominally identical photodiodes (PD) (each having 15 GHz bandwidth and an integrated trans-impedance amplifier, TIA). We note that standard 10G photodiodes would suit as well. The polarization states of the LO and of the signal were mutually aligned by a manual polarization controller (PC). The three output photocurrents (i_k) were sampled by a real-time oscilloscope (RTO, 13 GHz analogue bandwidth, 40 GSa/s) and then processed off line. The ASK signal envelope was recovered by squaring and summing the three i_ks via software in the RTO (as shown in Fig. 2) [6], [11], [12]. The bit error ratio (BER) was computed off-line comparing bit-by-bit the received sequence against the transmitted one by means of an ad hoc SW routine run by the RTO processor.

4. Results and Discussion

As already discussed, in our approach FM-AM conversion is obtained in the coherent receiver. The OSR filter is replaced by three identical electrical low pass filters (EFs in Fig. 2), one for each current i_k, placed between the PIN + TIA and the envelope detector. The reshaping EFs were implemented by using a built-in digital low pass filter function (Gaussian shape, linear phase) in the RTO before digital data processing. The LO (power about 10 dBm) was tuned so as to match the wavelength of the “1”s. In this way, the low pass EF lets “1”s through and attenuates the red shifted “0”s. Then the modulation peak-to-peak amplitude of DFB-1 was set to the appropriate value giving 5 GHz of adiabatic chirp (Vpp=1.4 V), in order to obtain the dispersion managing effect, as discussed in Section 2.

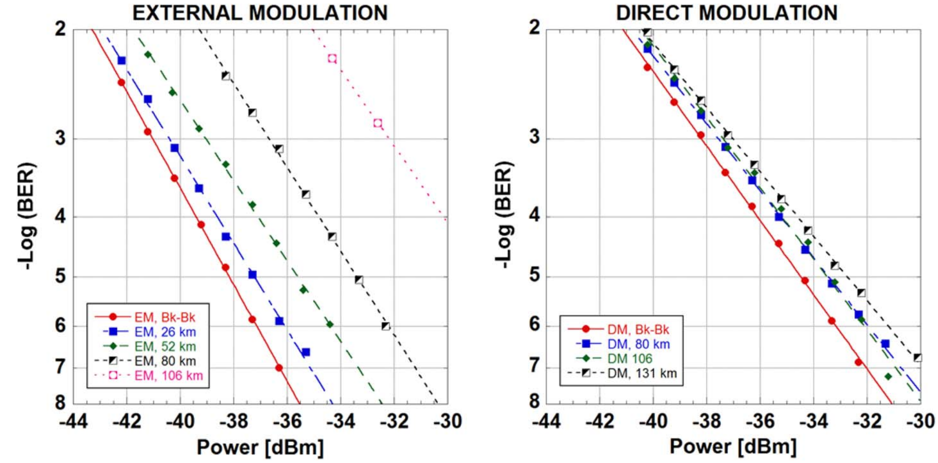

Fig. 4. Back-to-back and propagation performance of external modulation (left) and of direct modulation with coherent spectral reshaping (right).

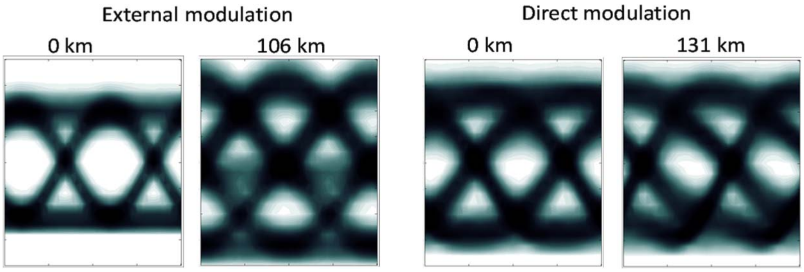

Fig. 5. Measured eye diagrams.

We found that a very good system performance (using 5 GHz adiabatic chirp) is obtained by choosing a low pass filter bandwidth of 3 GHz, which is not far from half the band-pass of the OSR used in [8] (7.1 GHz FWHM). Fig. 3 shows the electrical spectrum of DFB-1, as measured at point A of Fig. 2, for 1 Gbit/s (left) and for 10 Gbit/s (right) modulation rates before (blue lines) and after (red lines) 3 GHz electrical filtering. The 5 GHz frequency shift between "1"s and "0"s is clearly seen in the plot on the left, while in the case at 10 Gb /s modulation, the chirp peak is merged into the modulation bandwidth. A detailed characterisation of system behaviour against variations of low pass filter bandwidth and of other system parameters will be discussed later on in this paper.

The system performance was tested for different transmission distances up to 131 km of G.652 fiber by measuring the corresponding BER versus received power. The performance of the proposed solution (direct modulation, DM) was compared with that obtained when DFB-1 is externally modulated (external modulation, EM) by a chirp free $LiNbO_3$ Mach–Zehnder modulator (MZM), taken as a benchmark. In this second case DFB-1 was operated continuous wave (CW). The MZM output power was −6 dBm, 7.8 dB less compared to the DM-DFB laser case, due to the losses of the polarization controller and the MZM. In this case the optimum value for the EF bandwidth was 10 GHz. The obtained BER curves are shown in Fig. 4. It is worth noting that the back-to-back sensitivity at the FEC level $(\mathrm{BER} = 1.8 \times 10^{-3})$ for EM (left plot, red curve) is as low as −41 dBm, showing the clear advantage offered by coherent detection. As can be seen, our solution (DM, right plot) shows a sensitivity of −38.2 dBm with a back-to-back penalty of about 3 dB with respect to EM. This can be partially explained by looking at Fig. 5 where eye diagrams (recorded at point B in Fig. 2) in back-to- back (0 km) and after transmission are shown for EM (left) and DM with coherent chirp management (right). The eye diagram at 0 km

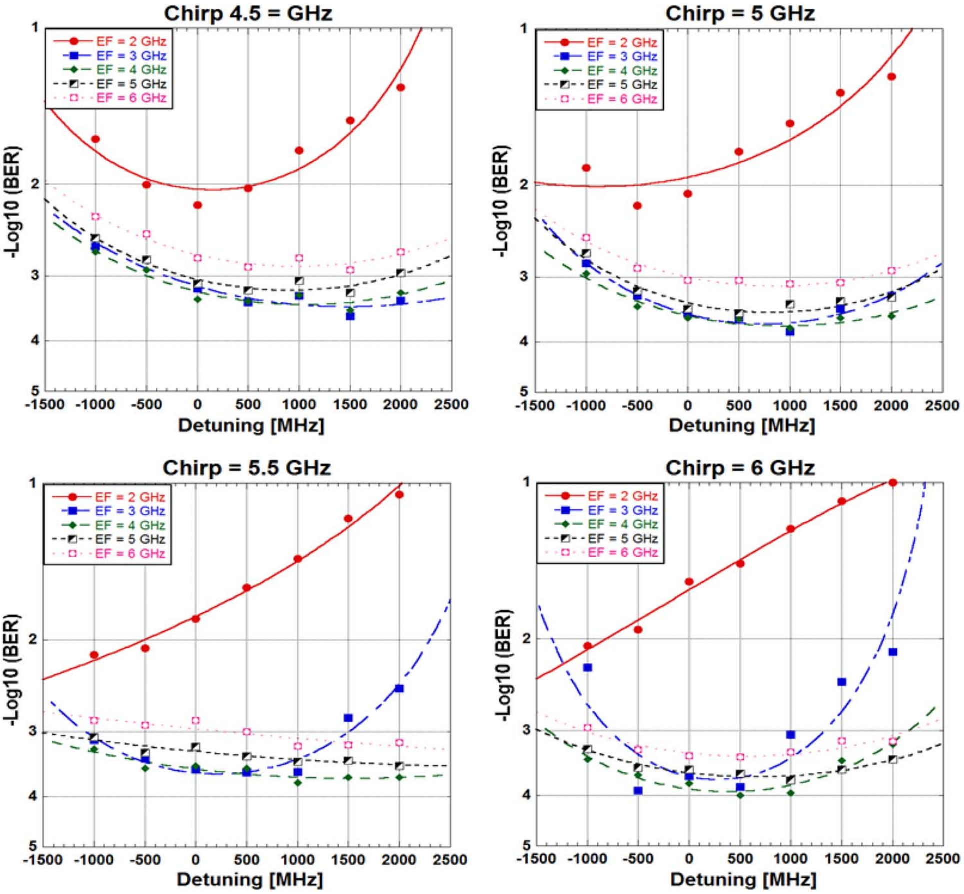

Fig. 6. System robustness in terms of BER vs. detuning for different values of adiabatic chirp and of EF bandwidth.

for DM shows slow wave fronts, because DFB-1 is a low cost DFB laser designed for 2.5 Gb/s. However at 80 km DM with electrical filtering out-performs the EM transmitter by about 1 dB. At 106 km the lower output power of the EM limits received power to −32.3 dBm with a BER of 1.4×10^{-3} (no EDFA was used in the experiments). On the contrary, with the proposed solution, a span length of 131 km can be reached with only 1 dB of power penalty with respect to the back to back. without the need of EDFAs and relying only on the high sensitivity of coherent detection. As shown in Fig. 5 the eye diagram of EM is strongly degraded after 106 km, while the DM chirp managed approach allows to obtain a clear open eye diagram up to 131 km.

In [13], Matsuo *et al.*, presented a CM system based on a FM laser, and an OSR filter at the transmitter and an APD receiver for direct detection. They obtained a sensitivity of −32 dBm in back to back at $\text{BER} = 1.0 \times 10^{-3}$ and of −30 dBm after 140 km transmission distance at the same BER level. Moreover, an EDFA was used for links longer than 100 km. Compared to these results our approach based on a coherent receiver has a better sensitivity (−38.2 dBm in back to back and −36.5 dBm after 131 km of SMF fibre) and does not require any EDFA.

To assess system robustness, we also tested the proposed solution against variations of critical system parameters. In particular we considered variations of 1) the detuning between signal laser and local oscillator (LO), 2) the DM-laser chirp, and 3) the EF bandwidth. In all cases, the system performance was measured at the maximum span length of 131 km at a fixed received power (−35 dBm). The variation of the BER was measured for different values of the laser chirp and of the filter bandwidth as a function of signal-LO frequency detuning. The obtained results are reported in Fig. 6.

We experimentally investigated four different DM-laser chirp values (4,5; 5; 5.5, and 6 GHz), each for five different EF bandwidth values (2, 3, 4, 5 and 6 GHz) and for seven different signal-LO detuning values (−1000, −500, 0, 500, 1000, 1500, and 2000 MHz). As can be seen, the system shows a good degree of tolerance to the variations of these parameters. The best performance was measured for a DM-laser chirp of 6 GHz, EF bandwidth of 4 GHz and 500 MHz detuning, but a BER degradation of less than half a decade was recorded for detuning values ranging from −500 to 1000 MHz and for EF bandwidth values of 3, 4 and 5 GHz. Considering the slope of the BER curves reported in Fig. 4, half a decade of BER variation corresponds to less than 1 dB sensitivity penalty. A similar behaviour was observed for the other chirp values, even though in these cases the best performances are slightly worse than in the 6 GHz chirp case. For DM-laser chirp values above 5 GHz the sensitivity to the filter bandwidth increases rapidly.

As can be seen very good system performance can be obtained also for chirp values and filter bandwidths not exactly equal to those considered for optical chirp managed lasers. The performance differential is very small (fractions of a BER decade) and almost comparable with the repeatability of the BER measurements.

These results show that the system is quite robust against the variation of the considered parameters. Changes of less than 1 dB in system performance were observed when the LO detuning varied over an interval of 1.5 GHz around the optimal value, the EF bandwidth varied over a 2 GHz interval and when the chirp value was changed over an interval of 1 GHz. Therefore the proposed system does not require a very precise setting; this is an important feature in view of practical implementations. In fact the use of DM-DFB lasers is particularly appealing for LR-PON with target span $\geq$ 100 km as it avoids the losses associated with external modulators (7.8 dB in our case) and significantly reduces the transmitter costs.

5. Conclusion

In this work we experimentally demonstrated that strong resilience to chromatic dispersion can be obtained using a directly-modulated low cost DFB laser as a transmitter and exploiting a simplified homodyne coherent receiver with proper filtering at the intermediate frequency. This technique is equivalent to the optical filtering adopted in the classical Chirp Managed approach. The proposed technique offers the advantage of avoiding the insertion of “colored” optical filters either at TX or at RX. 10 Gbit/s ASK transmission experiments show that the proposed approach outperforms a chirp-free EM transmitter for propagation distances longer than 80 km. By using a simple DM-DFB laser as a transmitter we demonstrated 131 km 10 Gbit/s ASK transmission with a power penalty as small as 1 dB. Moreover, the system, although realized using off-the-shelf components, is robust and shows a good tolerance to variations of chirp, EF bandwidth and LO detuning. Less than 1 dB performance degradation (half a decade degradation in the BER value) was experimentally observed over a 1.5 GHz interval of variation of LO detuning, over a 2 GHz interval of variation of EF bandwidth and over a 1 GHz interval of variation of laser chirp. This feature is very attractive, since very tight control of system parameters is not required. The use of DM-DFB lasers is particularly interesting for LR-PONs with target reach $\geq$ 100 km as it saves the losses associated with external modulators (7.8 dB in our case) and significantly reduces the transmitter costs. We note that in principle ASK demodulation can also be implemented in this receiver by means of analog electronic circuitry without requiring DSP. Finally, it is expected that this approach can be useful also for digital coherent receivers, since the complexity of DSP can be reduced, lowering cost and power consumption.

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