Real-time 10Gbps Polarization Independent Quasicoherent Receiver for NG-PON2 Access Networks

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Abstract—In this paper, we propose and test experimentally a real-time 10 Gbps polarization independent quasicoherent receiver for NG-PON2 access networks. The proposed 10 Gbps quasicoherent receiver exhibits a sensitivity of -35.2 dBm after 40 km SSMF transmission with a commercial generic EML as transmitter. This sensitivity means a 14.9 dB improvement over a direct detection scheme with a photodiode after 40 km SSMF transmission. Therefore, the use of the proposed 10 Gbps quasicoherent receiver with the tested EML will provide a power budget of 35.64 dB (class E2) and a splitting ratio of 128 after the 40 km SSMF transmission. Finally, the proposed 10 Gbps quasicoherent receiver allows a colorless and optical filterless operation because wavelength selection is done by tuning the local oscillator wavelength and using electrical intermediate frequency filtering.

Index Terms—NG-PON2, TWDM, Coherent receiver, Access network, PON

I. INTRODUCTION

DURING the recent years, data traffic over optical access networks has grown exponentially. This data traffic growth will continue in the future because of the high bandwidth demand due to the expansion of current services such as streaming media, Internet of Things (IoT) and cloud computing; the development of new services using virtual and augmented reality technologies [1] and the convergence of wireless and optical access networks on the 5G paradigm [2].

In order to address the current and future data traffic requirements, the NG-PON2 standard for passive optical networks (PON) was recently released [3, 4]. The NG-PON2 standard is based on time and wavelength division multiplexing (TWDM) through four wavelength channels at a data rate of 10 Gbps per channel and providing an aggregated data rate of 40 Gbps.

The NG-PON2 standard has high demanding requirements for both network and devices in order to satisfy this growing user data traffic and the operators' necessities. The TWDM operation of NG-PON2 requires 10 Gbps colorless and tunable optical network units (ONU), as can be seen in Fig. 1. In addition, the NG-PON2 standard proposes optical distribution networks (ODN) with high splitting ratios, up to 256, and long transmission distances, up to 40 km. These high demanding technical requirements increase the cost of the ONU because of the necessity of using optical tunable filters, high sensitivity avalanche photodiodes (APD) [5, 6], optical amplifiers and high optical power and wavelength stable transmitting lasers.

Coherent technologies [7] have been researched during the recent years as a promising solution to satisfy these more and more demanding requirements of the optical access network. Cost-effective emitters have been proposed for coherent optical access networks as directly-phase modulated

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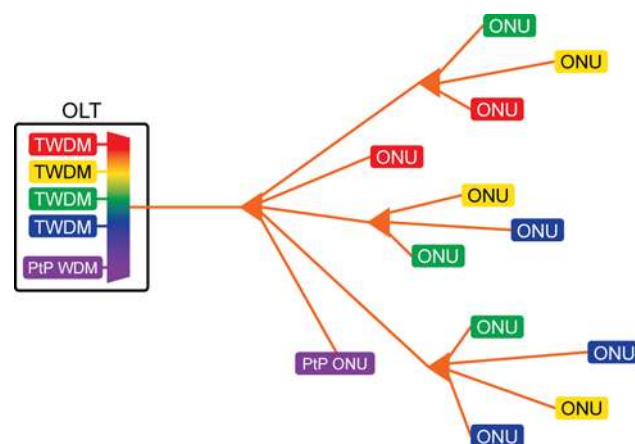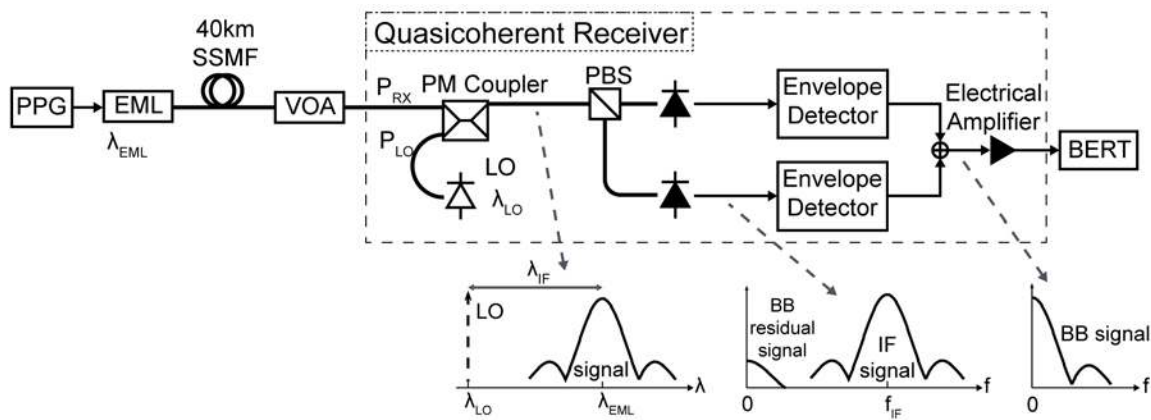
Fig. 1. NG-PON2 network.

Fig. 2. Experimental setup. Insets: LO and signal spectrum schematic, heterodyne downconverted signal and baseband received signal.

distributed feedback lasers (DFB) [8, 9], directly-phase modulated reflective semiconductor amplifiers (RSOA) [10, 11], intensity modulated vertical cavity surface emitting lasers (VCSEL) [12] or directly-phase modulated VCSELs [13]. In addition, several coherent receiver technologies have also been proposed and developed. These proposals have a special focus on polarization independence or polarization control as it is an issue for low cost coherent receivers. One of the first proposals was made by Glance [14] using a similar setup but designed for digital DPSK signals, when our proposal is managing analog signals. This same architecture has been proposed in other works for coherent optical access [15]. Other solutions based on different designs use 3x3 couplers [16], polarization scrambling at the transmitter [17] or Alamouti encoding at the transmitter side [18]. Additionally, coherent receivers for optical access networks demand as reduced as possible digital signal processing (DSP) [19], [20] after the optical reception in order to keep the ONU complexity as simple as possible.

This work proposes a real-time 10 Gbps polarization independent quasicoherent receiver for NG-PON2 access networks, extending and completing our previously published results presented in [21]. In particular, we will add to the previous results: the spectral characteristics of the source, the intermediate frequency shift for the receiver given the characteristics of the emitter, a comparison of the behaviour between the direct detection (DD) scheme and the quasicoherent receiver for back to back and 40 km links, and a discussion of the available power budget, addressing the performance of the receiver in terms of splitting ratio and the NG-PON2 class than can be fulfilled with it. We will see that the receiver allows an increase of its sensitivity in order to fulfil the NG-PON2 requirements without using APDs at the receiver or high power lasers at the transmitter and therefore achieving a cost effective receiver architecture adequate for the ONUs and the optical line terminals (OLTs) of a passive optical access network. In addition, the real-time 10 Gbps polarization independent quasicoherent receiver enables a colorless operation without expensive tunable optical filters and a real-time operation without additional DSP keeping a low complexity of the receiver.

II. EXPERIMENTAL SETUP

The schematic of the real-time polarization independent 10 Gbps quasicoherent receiver is shown in Fig. 2 and denoted as Quasicoherent Receiver. Fig. 2 also shows the experimental setup employed to test the quasicoherent receiver.

The first part of the 10 Gbps receiver consists of a polarization maintaining (PM) optical coupler, which is used to combine the receiver signal and the local oscillator (LO). The LO is connected to the PM coupler in such a way that at the output the power is splitted at 50% in both principal polarization axes. The LO consists of an external cavity laser (ECL) with 100 kHz linewidth and -145 dB/Hz Relative Intensity Noise (RIN). The ECL was selected as LO because it eases the tuning of the emitting wavelength and its output optical power. We have also tested several Distributed Feedback (DFB) lasers as LO presenting linewidths up to ~10 MHz and we have found that the sensitivity results are basically the same. These DFB lasers had also RIN values in the range of, or lower than -145 dB/Hz so the noise characteristics of the DFBs are similar to these of the ECL.

After the optical coupler, the signal and LO go through a polarization beam splitter (PBS) and are received using two high bandwidth photodiodes (PD). The LO wavelength (λ_{LO}) is shifted away a value of λ_{IF} from the signal wavelength (λ_{EML}) in order to downconvert the received signal to an intermediate frequency (IF) when the signal and LO are received with the PDs, as is depicted in the inset of Fig. 2. Two types of PDs have been employed in this article. The first analysis of the quasicoherent receiver has been made using two standard commercial PDs presenting an electrical bandwidth of 23 GHz, as the result presented on [21]. The sensitivity and the intermediate frequency shift measurements have been made employing two slightly better sensitivity commercial PDs with 33 GHz electrical bandwidth, but maintaining the same IF and measurement conditions. These new PDs will permit in the future to obtain higher intermediate frequencies thus allowing future increases in the available user bandwidth.

The received intermediate frequency signal is then downconverted to baseband, as is shown in Fig. 2, employing
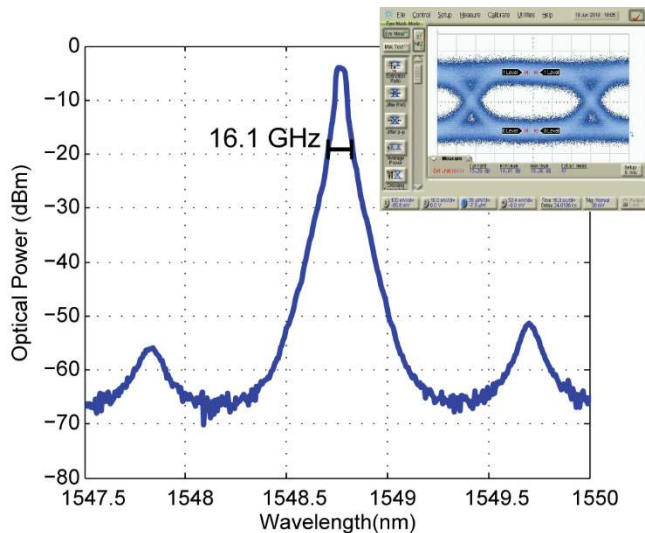
Fig. 3. Optical Spectrum of TX signal. Inset: Eye diagram of TX signal.

Fig. 4. BER versus received power for 10Gbps quasicoherent receiver for different LO power.

two 10 Gbps ultra-wideband envelope detectors (ED) [21], similar to the ones presented on [22] but designed to support 10 Gbps signals. After the downconversion of the signals to baseband, both signals are electrically added and then amplified. Finally, the Bit Error Rate (BER) is measured using a real-time BER test (BERT). Therefore, the 10 Gbps polarization independent quasicoherent receiver does not require any kind of digital signal processing (DSP) after the reception to measure its performance as is generally needed in heterodyne coherent receivers, allowing a simple real-time operation for a quasicoherent scheme.

The designed testbed consists of a 10 Gbps transmitter, 40 km of Standard Single Mode Fiber (SSMF) and a variable optical attenuator (VOA). The transmitter used to test the described real-time 10 Gbps polarization independent quasicoherent receiver is a commercial, 80 km-10 Gbps bandwidth external modulated laser (EML) emitting 0.44 dBm optical power. The transmitter is modulated with a 10 Gbps non-return to zero (NRZ) data signal coming from a pulse pattern generator (PPG). The optical spectrum of the transmitted signal is shown Fig. 3. We can see that the λ_{EML} is 1548.75 nm and the bandwidth at -15dB (BW$_{-15dB}$) is 16.1 GHz. The inset of Fig. 3 shows the eye diagram of the transmitted signal and from it the extinction ratio is estimated to be 15.28 dB.

Fig. 4 shows how the evolution of BER curves as a function of the received power (P_{RX}) for different LO optical powers (P_{LO}), similar to the measurements made in [1]. P_{LO} is varied from 6.5 dBm to 14.5 dBm in steps of 2 dB. The P_{LO} increment causes a reduction of the required P_{RX} to obtain a given BER value i.e. an improvement of the sensitivity of the 10 Gbps quasicoherent receiver. As the curves depicted in Fig. 4 are nearly parallel straight lines, the P_{RX} reduction is the same almost for any measured BER. For the first 2 dB of P_{LO} increase, the improvement of the sensitivity is around 1.25 dB. This improvement gets saturated after increasing the P_{LO} over 10.5 dBm and the required P_{RX} reduction falls approximately to 0.75 dB for the last 2 dB of P_{LO} increment. This behavior is compatible with a receiver limited by shot noise, which is
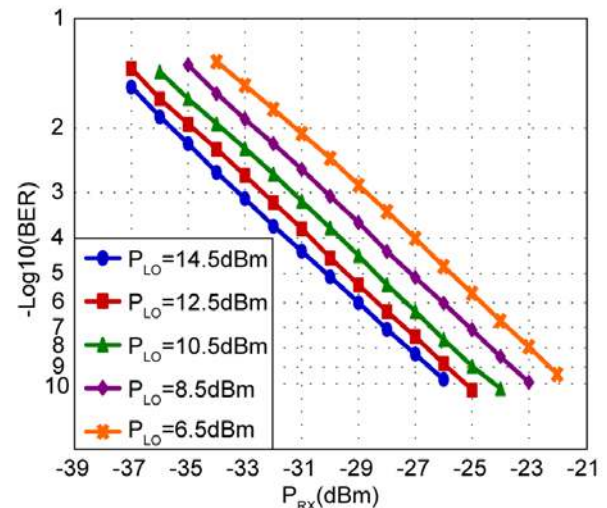
going to be higher than the LO-RIN that will have a greater contribution to the overall noise as our receiver is not balanced. As a consequence of this characterization, the increment of 8 dB of the P_{LO} causes an accumulated P_{RX} reduction of 4 dB and therefore a P_{LO} of 14.5 dBm will be used because it provides the best BER value for any received optical power.

III. RESULTS AND DISCUSSION

In this section, the performance of the 10 Gbps quasicoherent receiver is tested and discussed. The performance analysis is based on the receiver sensitivity, the maximum IF shift allowed by the quasicoherent receiver and its relation with the maximum spectral excursion (MSE) of the transmitters, and the achievable power budget.

The receiver sensitivity has been defined as the minimum received power with a maximum BER of 10^{-3}, which is the maximum allowed BER by the forward error correction (FEC) as stated on the NG-PON2 standard [4]. Fig. 5 shows the receiver sensitivity curves for the proposed quasicoherent receiver and a direct detection scheme (DD) for back-to-back (BTB) and for 40 km SSMF transmission. The DD reception is performed using a PD with the same features than these used in the quasicoherent receiver and the same electrical amplifier in order to have a useful comparison.

The receiver sensitivity exhibited by the 10 Gbps quasicoherent receiver is -35.2 dBm for BTB transmission. The quasicoherent receiver exhibits a null dispersion penalty after 40 km SSMF transmission, as it can be seen from figure 5, due to the use of an EML in combination with the filtering characteristics of the envelope detector. The BTB receiver sensitivity with DD is -20.9 dBm and exhibits a dispersion penalty of 0.6 dB after 40 km SSMF transmission. Therefore, the proposed 10 Gbps real-time polarization independent quasicoherent receiver has a 14.3 dB sensitivity improvement in comparison with a DD scheme. This improvement increases to 14.9 dB when the dispersion penalty of 40 km SSMF transmission is included. Typical avalanche photodiodes
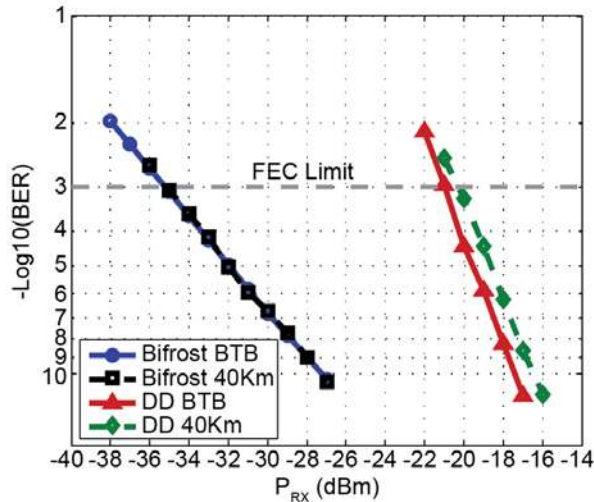
Fig. 5. BER vs. received power for 10Gbps quasicoherent receiver and DD.

Fig. 6. Intermediate frequency shift for 10Gbps quasicoherent receiver.

(APD) only provide an improvement between 5 and 10 dB in comparison with the PDs [6, 7].

The maximum IF shift is defined as the maximum IF range that provides at least a target receiver sensitivity. This IF range varies due to the electrical bandwidth of the PDs, which in these measurements was of 33 GHz. Fig. 6 shows the receiver sensitivity of the 10 Gbps quasicoherent receiver for each IF generated after the PDs. The sweep of the IF has been done varying the LO wavelength and keeping the transmitter (TX) wavelength fixed for simplicity. These results would be the same if the TX wavelength was varied and the LO wavelength was kept fixed. The maximum IF shift for a receiver sensitivity of -34 dBm is 17.2 GHz. This maximum IF shift can be increased to 20 GHz with 1 dB of penalty and to 23.4GHz with 2 dB of penalty as can be seen in Fig. 6.

The maximum spectral excursion (MSE) of a transmitter is defined as "the absolute difference between the nominal central frequency of the wavelength channel and the -15 dB point of the transmitted spectrum furthest from the nominal central frequency" [5]. Although the MSE is a parameter related to the transmitter, it is relevant for the 10 Gbps quasicoherent receiver because it may determine its colorless and optical filterless operation, which are desired characteristics for a NGPON2 receiver. In a PON architecture, the nominal central frequency or wavelength of the transmitter may change due to many different causes, being a burst transmitter one of them, and the bit rate and chirp characteristics of the transmitter will determine its BW_{-15dB}. The 10 Gbps quasicoherent receiver allows a colorless operation by using the LO as the selector of the receiver wavelength channel, provided that the signal spectrum does not vary too much. The optical filterless operation of the 10Gbps quasicoherent receiver is achieved because the LO downconverts the selected channel to IF and then the signal is electrically filtered, but an increase of the transmitter signal spectrum may cause an additional excursion of the IF. So, the proposed receiver design may avoid expensive optical tunable filters on the receiver to obtain a colorless operation, but clearly the maximum IF shift of the quasicoherent receiver is
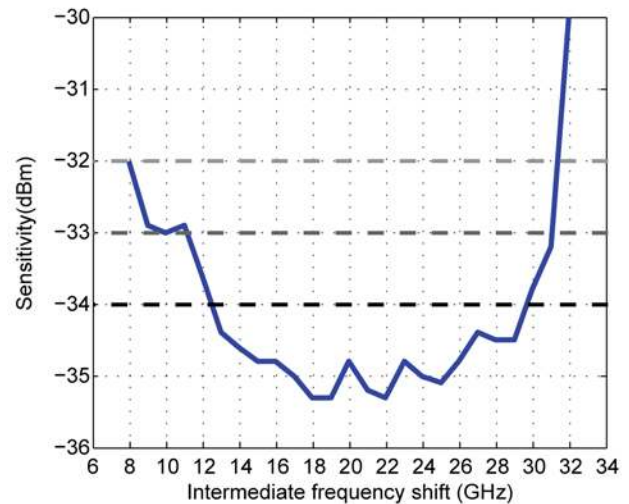
relevant in relation with the MSE of the transmitter.

The MSE sets a limit on the transmitter wavelength fluctuation because its value is the combination of its wavelength variation and the BW_{-15dB} of the transmitted signal. Therefore, the MSE value sets the maximum IF fluctuation allowed for the 10 Gbps quasicoherent receiver to operate as a colorless one. The NG-PON2 standard defines a MSE of ±12.5 GHz for 50 GHz channel spacing and a MSE of ±20 GHz for 100 GHz channel spacing. Therefore, the maximum IF shift is dependent on the sensitivity of the receiver but also on the variation of the spectrum of the transmitted signal, as it is important that the complete spectrum of the signal fits within the limits of the maximum IF shift of the receiver.

The MSE values defined within the NG-PON2 standard and the 10Gbps quasicoherent receiver measured MSE compatibilities are summarized on Table I. The 10 Gbps quasicoherent receiver will provide a receiver sensitivity of -34 dBm being compatible with transmitters that have an MSE of ±16.65 GHz. Therefore, the 10 Gbps quasicoherent receiver can operate with transmitters designed for 50 GHz channel spacing network on the NG-PON2 standard. If the required receiver sensitivity can drop to -32 dBm, the 10 Gbps quasicoherent receiver will be compatible with transmitters with a MSE of ±19.75 GHz. This MSE value is close enough to the MSE requirement of the transmitters that operate with 100 GHz channel spacing of the NG-PON2 standard and so compatible with them.

An important parameter for NG-PON2 networks is the power budget of the link because it will determine the maximum reach and splitting ratio of the deployed network

TABLE I
MSE VALUES FOR UPSTREAM TRANSMITTERS AND QUASICOHERENT RECEIVER COMPATIBILITY

Channel Spacing	50 GHz	100 GHZ
NG-PON2 requirement	±12.5 GHz	±20 GHz
Quasicoherent receiver with P_{RX} of -34dBm	±16.65 GHz	-
Quasicoherent receiver with P_{RX} of -32dBm	±19.75 GHz	±19.75 GHz

TABLE II
POWER BUDGET, SPLITTING RATIO AND NG-PON2 CLASS SUMMARY

	Testing EML			Standard NG-PON2 TX		
	Power budget	Splitting ratio	NG-PON2 class	Power budget	Splitting ratio	NG-PON2 class
Quasicoherent receiver with the best sensitivity value	35.64 dB	128	E2	37.2 dB	128	E2
Quasicoherent receiver compatible with 50 GHz channel spacing	34.44 dB	64	E1	36 dB	128	E2
Quasicoherent receiver compatible with 100 GHz channel spacing	32.44 dB	64	N2	34 dB	64	E1
DD – PIN (as measured in this work)	21.34 dB	8	-	22.3 dB	16	-
DD – APD [23]	30.94 dB	32	N1	32.5 dB	64	N2

and so the profit that its exploitation will provide to the operator. In this case, we will define the power budget as the difference between the transmitted power and the receiver sensitivity after 40 km SSMF transmission. The dispersion penalty has been subtracted from the power budget in order to show just the allowed optical path losses. In the power budget calculation, the fiber attenuation is considered as 0.25 dB/km and the splitter losses are considered as 3.5 log2(M) dB with M being the splitting ratio [4].

We will discuss the obtainable power budget using the tested EML as the transmitter but also using typical NG-PON2 transmitters, which provide higher optical powers. These other transmitters have not been measured in this work, but their emitted optical power nominal values, as shown in the standard, have been used as a comparison.

The proposed 10 Gbps quasicoherent receiver and the EML employed for the setup are able to provide an optical power budget of 35.64 dB for a -35.2 dBm receiver sensitivity. This power budget allows to fulfill the requirements of E2 class of the standard. We will compare these values with the optically unfiltered PIN measured in figure 5 (DD-PIN), and also, for a more realistic comparison, with an APD-based optically filtered receiver [23], which presents a sensitivity of about -30.5 dBm. For the first case, if a DD-PIN scheme is used, the power budget drops to 21.44 dB and in this case it is not able to fulfill the required optical path losses (OPL) of any NG-PON2 class. If we consider the DD-APD receiver, the available power budget of 30.94 dB would fulfill the maximum OPL of NG-PON2 N1 class, which is 29 dB. In terms of splitting ratios, the proposed 10 Gbps quasicoherent receiver would allow a splitting ratio after 40 km SSMF transmission of 128, whereas the DD-PIN PIN would only allow a splitting ratio after 40 km SSMF transmission of 8, which would increase to 32 in the case of using the APD-based receiver.

The EML that we have used on the tests does not fulfill the emitting power requirements of the standard, which has a lower limit of +2 dBm. If a standardized NG-PON2 transmitter is employed, the minimum emitted optical power is +2 dBm. In this case, and considering only emitted optical power variations, the power budget provided by the proposed 10 Gbps coherent receiver would be of 37.2 dB after 40 km SSMF transmission. The combination of a standardized NG-PON2 transmitter with the proposed 10 Gbps quasicoherent receiver would fulfil the E2 class of the NG-PON2 standard and would allow a splitting ratio after 40 km SSMF transmission of 128, only 0.8 dB below the optical power necessary to obtain the logical NG-PON2 limit of 256 users. If this standardized NG-PON2 transmitter is received using DD-PIN, the optical power budget falls to 22.3 dB, which does not fulfil any NG-PON2 class and will only allow a splitting ratio after 40 km SSMF transmission of 16. If the DD-APD receiver is used, the N2 class can be fulfilled and the splitting ratio after 40 km SSMF transmission will increase to 64.

Therefore, the proposed 10 Gbps quasicoherent receiver improves the power budget in comparison with the tested DD scheme using a PIN and even with the one that can be expected using an APD-based receiver. This improvement is translated on the fulfillment of a higher NG-PON2 class and a larger splitting ratio after 40 km SSMF transmission.

These power budget values of the 10 Gbps quasicoherent receiver and the direct detection scheme for the testing EML and for a +2 dBm optical power standard NG-PON2 transmitter are summarized on Table II, showing the allowed splitting ratios and the NG-PON2 OPL class compatibility.

In a multiwavelength scenario, as is required for the NG-PON2 standard, the transmitted wavelengths can fluctuate in the range defined by the MSE as was stated previously. In addition, the maximum transmitted wavelength variation is related with the sensitivity of the proposed 10 Gbps quasicoherent receiver as we have analyzed before. Thus, the power budget in a multiwavelength scenario will also be related with the MSE and so with the channel spacing.

A channel spacing of 100 GHz imposes a sensitivity of -32 dBm because of the MSE requirements, as has been explained previously. So, the power budget with a channel spacing of 100 GHz will be of 32.44 dB with the testing EML and around 34 dB with a standardized NG-PON2 transmitter. These power budgets allow to fulfill the N2 and E1 classes, respectively, and they will allow splitting ratios of 64.

If the used channel spacing is 50 GHz, the sensitivity improves to -34 dBm and so the power budgets will be better. The power budget will be of 34.44 dB when the transmitter is the testing EML and around 36 dB if a +2dBm standardized NG-PON2 transmitter is used. Thus, the E1 and E2 classes are fulfilled with these respective power budgets allowing splitting ratios of 64 and 128 respectively.

IV. Conclusion

A real-time 10 Gbps polarization independent quasicoherent receiver for NG-PON2 access networks has been presented in this paper. This real-time quasicoherent reception technique is a promising technology for NG-PON2 access networks that allows to solve the most demanding requirements of the NG-PON2 standard.

The proposed 10 Gbps quasicoherent receiver shows a sensitivity of -35.2 dBm after 40 km SSMF transmission. This sensitivity provides an improvement of 14.3 dB in comparison with DD with a PD after the same 40 km SSMF transmission. In addition, it will be better even with the 5-10 dB of improvement that an APD would provide.

The 10 Gbps quasicoherent receiver sensitivity will allow a power budget of 35.64 dB when the testing EML is used or 37.2 dB when a standardized NG-PON2 transmitter would be used. These power budgets will allow to fulfill the E2 OPL class of the NG-PON2 standard, respectively, whereas direct detection with a PD will not fulfil any OPL classes of NG-PON standard. In addition, the power budgets of the 10 Gbps quasicoherent receiver will give rise to a splitting ratio of 128 in comparison with the 8 and 16, respectively, that will allow direct detection with a PD. Even if an APD is employed for direct detection, the 10 Gbps quasicoherent receiver will increase the splitting ratio at least by a factor 2.

In addition, the proposed 10 Gbps quasicoherent receiver allows a colorless and optical filterless operation, which is compatible with NG-PON2 transmitters. The colorless operation is possible due to the channel selection done using the tunability of LO and the electrical IF filtering. If the transmitter has a MSE compatible with 50 GHz channel spacing, the quasicoherent receiver will provide a sensitivity of -34 dBm. Whereas the provided sensitivity will be -32 dBm if the transmitter has a MSE compatible with a 100 GHz channel spacing.

In conclusion, the proposed real-time 10 Gbps polarization independent quasicoherent receiver is a promising receiver for NG-PON2 access networks increasing the available power budgets and allowing colorless and filterless operation compatible with NG-PON2 transmitters.

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