Demonstration of a 10 Gbit/s Long Reach Wavelength Converting Optical Access Network

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***Abstract*—This paper demonstrates a 10 Gbit/s wavelength converting access network utilising a centralised optical processing unit that consolidates multiple low cost PONs onto a DWDM backhaul. The centralised processing unit functions as an amplifier, wavelength converter, pre-chirping stage and optical burst equaliser to map legacy PONs onto a DWDM grid for efficient backhaul transmission and to ease the dynamic range requirement of the 10 Gbit/s burst-mode receiver at the optical line termination (OLT). The dispersion limited performance, wavelength tolerance, and burst-mode dynamic range are evaluated demonstrating a maximum range of 62 km for 20 nm of input wavelength variation and a dynamic range of up to 22 dB.**

***Index Terms*—PON, Wavelength Conversion, DWDM, XPM.**

I. Introduction

THE access network bandwidth required by end users is ever increasing and the deployment of Passive Optical Networks (PON) has already begun to gather pace to tackle this demand. The successors to 1 Gbit/s and 2.5 Gbit/s services such as 10GEPON and XG-PON are already being trailed and deployed. In addition to high data rates, these Next Generation PONs (NG-PON) will offer higher user count and extended reach [1]. From the network operator's point of view, it is highly desirable to fully exploit and re-use the existing investment in fibre infrastructure [2], creating a persuasive argument for hybrid PON architectures that provide an evolution from TDM/PON by enabling WDM backhauling and long-reach while supporting the next generation of high data-rate access networks [3]. Some of these properties were proposed and demonstrated by the long-reach optical access network [4], wavelength converting access network [5] (consolidation of PON and WDM backhaul at 2.5Gbit/s), and the PIEMAN project [6] (long-reach and WDM but re-engineering of ONUs required in the access network). However, to further improve the cited access network schemes, a new architecture is required that integrates access and metro networks into one all-optical system, reducing the number of network elements and access/metro interfaces and increasing the backhaul capacity by using DWDM in an extended backhaul fibre of up to at least 60 km in length. Such a network can potentially lead to significant operational savings by reducing power consumptions as well as the footprint of the network [7].

Although many researchers propose a move to a true WDM-PON, this approach would require a significant change in the optical infrastructure making a gradual transition from current PONs difficult. From a service roll-out point of view, a technique that is backward compatible with existing PON architectures and allows the use of low cost Optical Network Units (ONUs) at the customers' premises would be logistically and economically advantageous. Previous work [5] proposed the use of all optical wavelength conversion to integrate multiple TDM PONs into a hybrid TDM, DWDM backhaul for 2.5 Gbit/s GPON. In this work we upgrade this system to the next generation of 10 Gbit/s optical access networks while maintaining backwards compatibility. This increment in bit-rate presents a number of challenges, requiring an all-optical processing unit that not only just amplifies and converts to a DWDM grid as previously demonstrated [5], but also pre-chirps the signal to allow long-reach transmission and suppress optical packet level fluctuations to relax the requirements of the upstream burst-mode receiver. Although O/E/O solutions are possible involving a high-dynamic burst-mode receiver, long-reach laser transmitter and associated electronics, we believe that an all optical solution is advantageous because of the bit rate transparency and the addition of pre-chirping and burst-level which reduces the receiver requirements.

In this paper, we experimentally demonstrate a proof-of-concept 10 Gbit/s Wavelength Converting Optical Access Network (WCOAN) with up to 62 km DWDM backhaul and centralised all-optical processing. Section II describes the proposed architecture of the system and the Centralised Optical Processing Unit (COPU). The wavelength conversion, chirp, and dispersion characteristics of the COPU in relation to transmission distance are discussed and analysed in Section III. The overall system performance is studied in Section IV, along with the burst-mode experimental demonstration and results. A summary of this work is presented in Section V.

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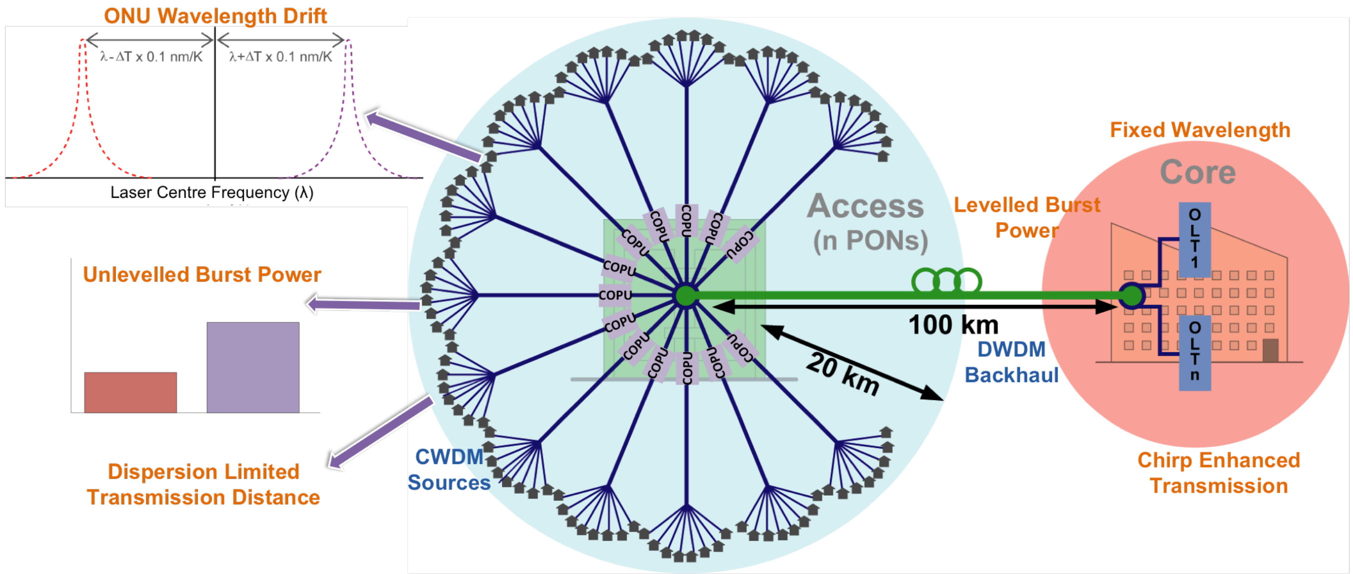

Fig. 1. Architecture of the proposed PON architecture for the integration of multiple CWDM PON segments into a common DWDM transmission backhaul. This architecture uses COPUs as intermediate all-optical processors and it is an extension of the architecture presented in [5].

II. Integrating 10 Gbit/s TDM-PON with a DWDM Backhaul

A. System Architecture

The principal challenge for both WDM-PONs and hybrid TMD/WDM PONs is to offer diverse upstream wavelengths available to every PON segment without having customized ONUs. In a standard 10G-EPON or XG-PON, the components used in both upstream and downstream directions are tolerant to wavelength drifts of ±10 nm without affecting the performance. This requires wavelength plans with 20 nm CWDM bands separating the up- and down-stream directions. However, when DWDM backhaul wavelength allocations are implemented, tight control of backhaul section wavelengths is required to fit multiple channels within the EDFA gain window. In addition, Arrayed Waveguide Gratings (AWGs) are commonly used to separate and recombine the multiple wavelengths for backhaul transmission. If a signal wavelength drifts out of its assigned AWG channel due to an unstable wavelength source, the signal will be lost to the receiver. Our architecture enables the use of low cost, non-temperature controlled, "colourless" ONUs. The intermediate stage processing also allows chirp-enhanced transmission of the wavelength converted signal, enabling long-reach DWDM backhaul while maintaining compatibility with current PON passive power-splitting distribution architectures.

The concept of the proposed integrated TDM-PON with DWDM backhaul access network upstream is shown in Fig. 1, where the network can be thought of as two sections. The first is a passive feeder fibre network connecting each customer to the local exchange. This is constructed in an identical fashion to a traditional PON with distributed passive optical splitters. The main physical layer issues in this section are the high loss associated with the optical power splitter, the unlevelled burst due to ranging, and the wavelength drift of the ONU laser sources because of temperature variation of the un-cooled laser. In the middle part of the network, before the long-reach DWDM backhaul section, an exchange site is used for the consolidation of multiple PON networks. In such long reach architectures, optical amplification is typically used at the exchange site to enhance the transmission distance. In our proposal, we introduce at the exchange site COPUs (shown as purple squares in Fig. 1) to consolidate numerous burst-mode data streams with drifting wavelength and unequalled burst powers from each PON segment. These data streams are converted by the COPU to a set of stabilised WDM wavelengths with equalised burst-to-burst power for transmission over the long-reach backhaul fibre, which may be dual fibres for upstream/downstream transmission, reusing current core or metro network fibres, and may or may not include additional amplification.

B. The Centralized Optical Processing Unit (COPU)

The COPU is expected to meet three different requirements which are, namely, wavelength conversion, optical burst power equalization, and transmission distance enhancement. The proposed COPU, shown in Fig. 2, is composed of an optical burst power equalizer followed by a SOA-MZI wavelength converter (WC) which also introduces negative chirp to compensate for dispersion in the backhaul at 10 Gbit/s.

The optical burst power equaliser is based on a saturated semiconductor optical amplifier (SOA) to level bursts coming from ONUs at different distances from the exchange and reduce the receiver dynamic range requirement at the OLT [8]. Alternatively this could be achieved using an electronic automatic level control circuit between the cascaded SOAs [9]. The wavelength conversion process stabilises CWDM ONU wavelengths onto a fixed DWDM wavelength determined by the probe wavelength, achieving efficient backhaul transmission over a DWDM link. Cross Phase Modulation (XPM) is considered to be more effective than Cross Gain Modulation (XGM) because of its high conversion efficiency,

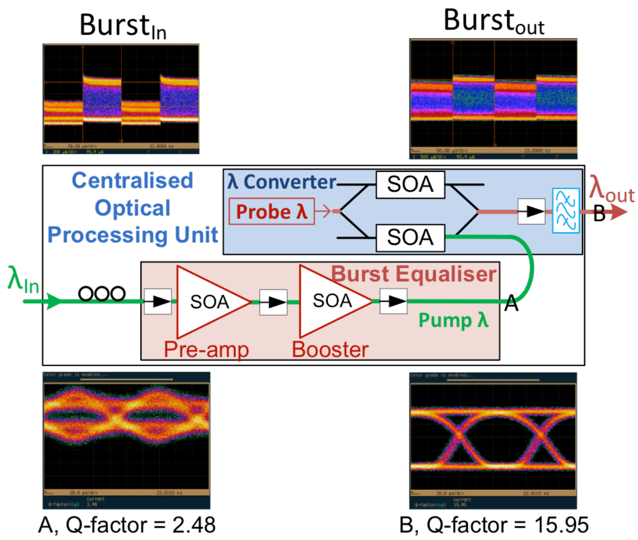

Fig. 2. The centralised optical processing unit (COPU) at the exchange/consolidation site capable of burst power levelling (pink block), wavelength conversion (blue block) and transmission distance enhancement (blue block). Signal distortion produced by the cascaded SOAs is regenerated in the wavelength converter. (inset A and B)

extinction ratio enhancement, and negative chirp characteristics [10]. At 10 Gbit/s line rates, the negatively chirped signal produced by XPM wavelength conversion process allows much longer transmission than the XGM process that was chirp limited to 11 km [11]. The next section will examine the burst power equalization, and the chirp and dispersion characteristics of this COPU.

III. System Characterisation

A. Experimental Set-up

The ONU in this proof-of-concept upstream access network demonstration was set up using a DFB laser with integrated EAM modulation using 10 Gbit/s 2^{31}-1 PRBS patterns. The ONU were controlled by an FPGA-based laser driver system capable of generating driving currents that turn the DFB lasers ON or OFF, resulting in alternating 125 µs bursts with 500 ns guard time between bursts. The configuration also allowed the transmitter to switch to continuous-mode operation, so that BER or eye diagrams can be monitored using the Bit Error Rate Tester (BERT) for system optimization.

The prototype COPU was realized with an optical power equaliser followed by a wavelength converter (WC). As shown in Fig. 2, the equaliser consists of two cascaded SOAs, the first SOA having > 20 dB gain to saturate the second SOA which has 14 dB gain and acts like a limiting amplifier. The equalised signal was then fed into an XPM wavelength converter based on a SOA-MZI configuration [12]. A probe laser was used to generate the desired output wavelength in the XPM wavelength converter. At the output of the COPU, an optical filter was used to simulate an AWG response, which aggregates multiple wavelength channels into the backhaul.

This experimental set up allows the characterisation and optimisation of the COPU devices for a range of input powers from −5 dBm to −35 dBm. The −15 dBm to −35 dBm power level is typical for PON systems with a > 32 way split and approximately −15 dB splitting losses. A standard DC-coupled PIN receiver was used in the characterisation. The clock synchronisation and data recovery in continuous-mode operation was provided by an Anritsu BERT. The upstream of 10G-class PONs is 1270nm, however, due to the limited availability of SOA-MZIs in this band the experiments are performed in the 1550nm band as a proof of concept. Techniques that allow cross-band conversion from 1300nm to 1500nm using 1300nm SOAs have been previously demonstrated [13].

B. Optical Burst Power Equalisation

To characterise the burst optical power equalisation of the COPU two burst-mode ONU signals at 1553.5 and 1556.3 nm were converted to the same probe wavelength at 1554.7 nm from two integrated DFB-EAM devices, used the experimental setup described in the previous section. Inset in Fig. 2 (inset Burst$_{In}$ and Burst$_{Out}$) shows the ONU bursts at the combiner and at the COPU output. It can be seen that their power difference is reduced from 5.53 dB to 0.54 dB, with continuous-mode signal power, measured after 22 km of backhaul fibre being 4.86 dBm and 5.40 dBm. Both processed signals showed an error free BER of 10^{-12} measured under continuous-mode operation.

C. Wavelength Conversion

To determine the effect of wavelength drift of an un-cooled ONU transmitter on the COPU's output signal performance, a wavelength tuneable ONU consisting of a tuneable laser followed by a Mach-Zehnder external modulator was used. The modulator bias of this wavelength tuneable ONU wavelength was adjusted so that its launched eye had the same 11 dB extinction ratio (ER) as the DFB-based fixed-wavelength ONU of previous experiment. Isolators at the output of the preamp and booster SOAs were used to prevent light and ASE noise from the subsequent SOA and SOA-MZI WC from interfering with the ONU signal and the booster SOAs operation. The BER performance was measured as a function of the ONU power at the input of the pre-amp SOA to determine the minimum input power level at which the wavelength converted signal output can remain error free

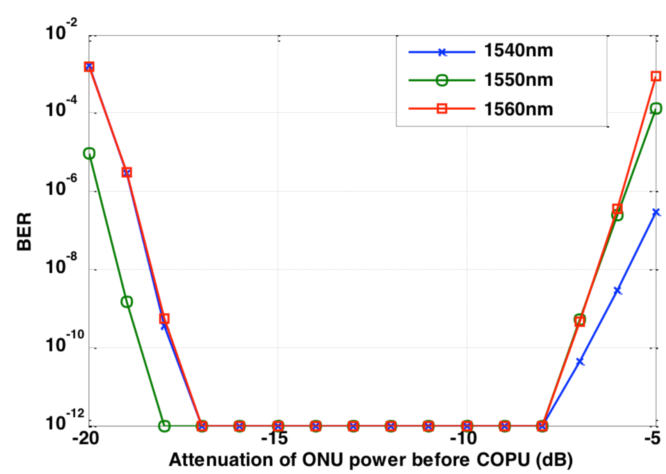

Fig. 3. The effect of the pump signal wavelength drift on the IPDR measured in terms of BER performance.

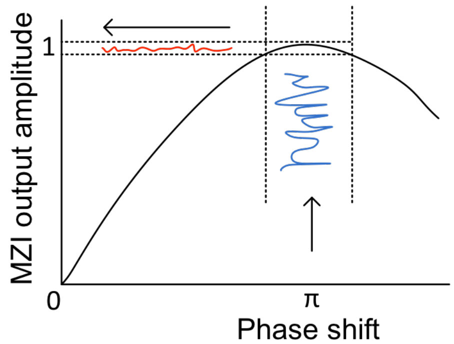

Fig. 4. Illustration of the relative SOA-MZI output amplitude as a function of induced phase shifts in the SOA. The amplitude noise is compressed when the phase shift is near π radians [10].

after 40 km backhaul transmission. A −5 dB attenuator was used to prevent the high-power signal after two stages of amplification from saturating the SOA-MZI wavelength converter. When the tuneable laser is tuned to another wavelength, the signal polarisation is slightly changed. Since the MZ modulator performance depends on the signal polarisation, the MZ modulator was re-aligned each time the wavelength was changed before the start of each set of Input Power Dynamic Range (IPDR) measurements. The WC used in this experiment is a prototype device which is polarization sensitive to the pump signal. This polarization dependency can account for up to 2 dB power penalty. Since polarisation insensitive SOA-MZI wavelength converters are available [14], to minimise the effect of polarisation dependent gain the polarisation controller at the input of the WC was also optimised.

The results in Fig. 3 show that wavelength drift does not change the system IPDR by more than 1 dB when the pump signal wavelength is detuned ±10 nm from the starting wavelength at 1550 nm. The IPDR is maximal at the centre wavelength of 1550 nm, with a possible ONU power variation of 10 dB. The IPDR decreases to 9 dB as the wavelength is tuned to 10 nm away from the centre. This is because the centre wavelength of 1550 nm was used as a reference to setup the system, and is the point at which the probe power was optimised for maximum pump power IPDR. Due to the non-flat gain and ASE noise profile of the cascaded SOAs, a detuning of wavelength from the optimised point also alters the probe power slightly, which can decrease the overall system IPDR.

D. Chirp Change in the COPU and Dispersion Penalty for Long-haul Transmission

In the COPU, a pre-amp SOA is used to amplify the ONU input signal power and a second saturated booster SOA is used to equalise the burst power. However, saturation of the booster SOA also produces un-wanted chirping of the ONU signal. The chirp generated can caused severe signal distortion due to the saturation induced self-phase modulation [15]. Nevertheless, the SOA-MZI device is capable of all-optical signal regeneration because the transfer function of the MZI structure has nonlinear amplitude to phase response. The gain induced phase shift and the output signal amplitude has a

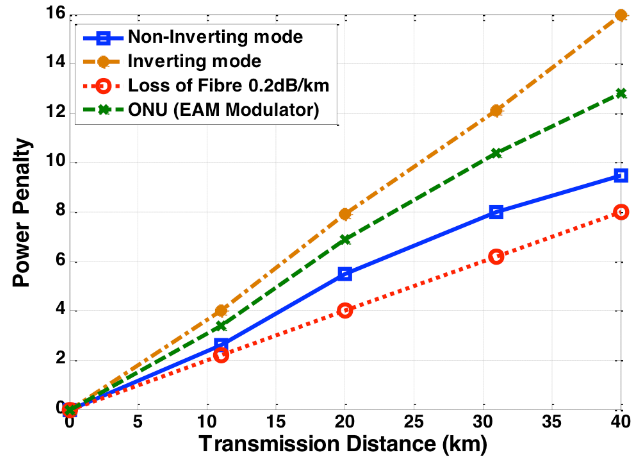

Fig. 5. Dispersion power penalty in the range from back-to-back to 40 km transmission distance.

sine-function like relationship. When the induced phase shift is near π radians, the input amplitude-noise-induced phase shift will be compressed [16], as illustrated in Fig. 4. Therefore, after the distorted signal has passed through the wavelength converter it will be reshaped.

Two example eye diagrams are plotted in Fig. 2 (inset A and B) showing the shape of the eyes at the input and output ports of the WC in the system. The chirping in the cascaded SOA stage causes severe signal gain distortion and amplitude noise at the input to the WC, closing the eye as seen in Fig. 2(inset A). However, the distortion does not affect the converted output signal Fig. 2(inset B), which is demonstrated by the fact that the Q-factor has increased from 2.48 before the wavelength conversion to 15.95 after the wavelength conversion. In this configuration the positive chirp arising in the SOA stages is not transferred to the wavelength converted output, because the WC's output chirp was determined by the device properties and the intensity of the input signal, regardless of input signal chirp parameter [17]. Biasing the MZI device at the positive or negative slope of its transfer function will give rise to the inverting and non-inverting mode of operation, which has either positive or negative chirp characteristics, respectively.

The non-inverting output signal from the wavelength converter is negatively chirped as a result of the pump induced refractive index change. This negative chirp can be exploited to reduce the penalty arising from dispersion in the backhaul fibre. The dispersion penalty for transmission over 40 km of fibre is shown in Fig. 5. The power penalty here is defined as the additional power required maintaining a BER of 10^{-10}. The negatively chirped signal shows a power penalty of 1.5 dB over the loss only reference, compared to penalties of 5 dB for a typical EAM based ONU and 8 dB for the inverted output of the wavelength converter, which exhibits a positive chirp. Measurements further than 40 km transmission distance were limited by the receiver sensitivity and the optical power at the output of the wavelength-converted signal.

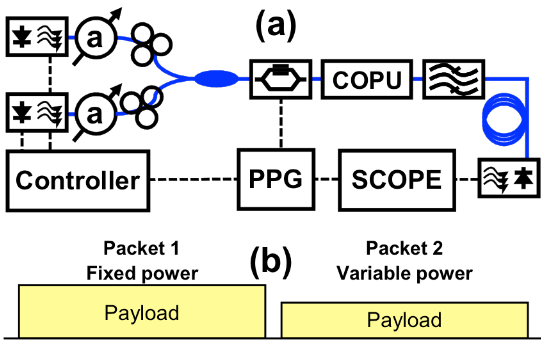

Fig. 6. (a) Burst-mode characterisation experimental setup with burst-mode transmitter, COPU, and digital burst-mode receiver. (b) Diagram of the two optical burst generated with this setup.

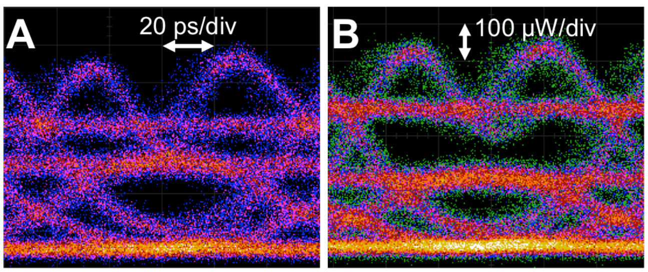

Fig. 7. Eye diagram at COPU output for two superimposed −15 and −25 dBm optical power burst for (a) maximum burst equalization (case A) and (b) intermediate burst equalization (case B).

IV. Experimental Burst-Mode System Performance

A. Experimental setup

In order to perform measurements of a typical PON system architecture environment, a complete burst-mode setup comprising a burst-mode transmitter and a digital burst-mode receiver was built. This setup, shown in Fig.6 (a), consists of two externally modulated DFB lasers at different wavelengths (1553.5 and 1556.3 nm). In order to create different burst powers, as illustrated in Fig. 6 (b), the two attenuators were configured in such a way that the optical power of the ‘loud’ burst was fixed at −15 dBm (equivalent to the ONU signal power after a 32-way power splitter), whilst the power of the ‘soft’ burst was swept from −5 dBm to −35 dBm in 1 dB steps. The 10 Gbit/s digital burst-mode receiver (DBMRx) used a standard DC-coupled PIN photodiode and an integrated trans-impedance amplifier (TIA) connected to a Tektronix DPO72004B real-time oscilloscope, sampling at 25 GS/s to digitise the signal for subsequent offline Digital Signal Processing (DSP) in MATLAB. The DBMRx performs clock-and-data recovery in the digital domain and has a fixed threshold equal to λ=0, which saves some DSP resources and produces an acceptable sensitivity penalty of only 0.5 dB compared to more complex adaptive thresholding algorithms [8].

The performance of the COPU can be adjusted by setting the WC bias point. In the prototype COPU used in this experiment, the two SOAs of the power equalizer had negligible PDL whereas the SOAs inside the MZI structure exhibited up to 2 dB PDL. The driving current of all the SOAs was kept constant and the WC bias point was then tuned by controlling the polarization of the input bursts rather than adjusting the driving current of the SOAs, as described in Section III.C of this paper. Thus, to optimize the COPU performance, two optical bursts of −15 dBm and −25 dBm were generated, and the bias point of the wavelength converter was set such as that the superimposed eye diagrams were as similar as possible (maximum burst power equalization, named case A), as different as possible (minimum burst equalization, named case C), or at an intermediate state (case B) [8]. Cases A and B are illustrated in Fig. 7. For clarity, only BER for optimization case A is presented in this work because case A maximizes the receiver sensitivity [8].

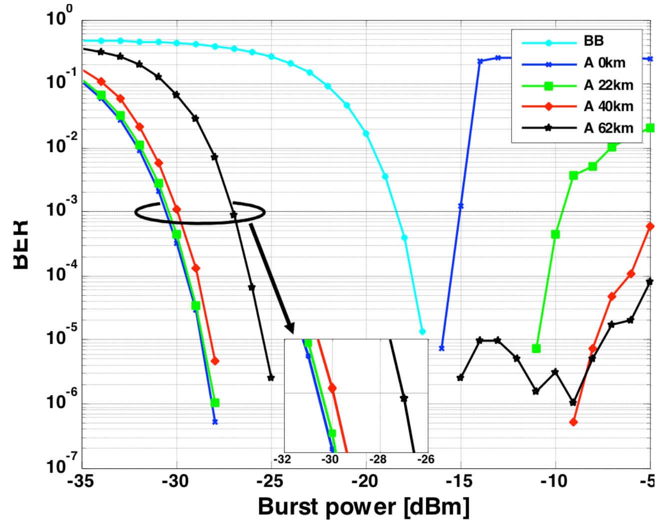

Fig. 8. Soft burst BER performance of the received signal in burst-mode operation at 0 km, 22 km, 40 km and 62 km fibre length, for back-to-back (BB) and COPU used as device under test.

B. Results and discussion

Fig. 8 shows the soft burst BER performance in burst-mode operation, for COPU optimisation case A (maximum burst power equalisation). The sensitivity is defined as the minimum soft burst power that produced a BER below the 10^{-3} reference, which is the FEC limit for 10G-EPON and it is higher than the XG-PON limit which is 10^{-4}. The BER of the loud burst was also monitored and it is always equal or below this limit. The back-to-back (BB) result in Fig. 8 indicates the DBMRx sensitivity in burst-mode operation, which is −18.4 dBm, and was measured by connecting the burst-mode transmitter straight into the DBMRx. The COPU increased the digital receiver sensitivity from the B2B by 12.2, 12, 11.5, and 8.6 dB for transmission distances of 0, 22, 40 and 62 km, respectively, as well as performing wavelength conversion and stabilization. The sensitivity of the digital receiver is maximal for the 0 km case and diminishes with transmission distance due to fibre losses and dispersion. When the input burst power is higher than −15 dBm, the overshoot of the receiver is worse for the 0 km case and improves with longer backhaul transmission distance due to the fibre dispersion compensating the negatively chirped output signal from the COPU.

V. Conclusion

A demonstration of a network architecture that consolidates multiple 10 Gbit/s CWDM PONs into a DWDM long reach backhaul was described and studied. The novel element of this architecture is the COPU, which contains a burst power equaliser stage, a wavelength converter, and a chirp-based dispersion compensator based on SOA-MZI XPM wavelength converter. For the first time, a full, burst-mode experimental upstream access network transmission system using the based COPU has been demonstrated. This system exhibits a lower chirp penalty than the standard fibre transmission over 40 km backhaul due to the chirp enhancement and subsequent compensation in the transmission fibre. It is also tolerant to ONU wavelength drifts of up to 20 nm wavelength with less than 1 dB input power dynamic range penalty.

Under burst-mode operation, the BER performance using a PIN-based DC-Coupled digital burst-mode receiver at 22, 40, and 62 km of unamplified backhaul distances were compared and sensitivities of −30.6, −30.4, and −27.0 dBm with overload points of −9.6, −5, and > −5 dBm were found, respectively. For a back-haul transmission distance of 40 km this meets the 32-split PR20 and PR30 10G-EPON specifications, thus allowing the consolidation for back-haul transmission of such PONs segments.

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