

# Performance of an optical equalizer in a 10 G wavelength converting optical access network

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**Abstract:** A centralized optical processing unit (COPU) that functions both as a wavelength converter (WC) and optical burst equaliser in a 10 Gb/s wavelength-converting optical access network is proposed and experimentally characterized. This COPU is designed to consolidate drifting wavelengths generated with an uncooled laser in the upstream direction into a stable wavelength channel for WDM backhaul transmission and to equalize the optical loud/soft burst power in order to relax the burst-mode receiver dynamic range requirement. The COPU consists of an optical power equaliser composed of two cascaded SOAs followed by a WC. Using an optical packet generator and a DC-coupled PIN-based digital burst-mode receiver, the COPU is characterized in terms of payload-BER for back-to-back and backhaul transmission distances of 22, 40, and 62 km. We show that there is a compromise between the receiver sensitivity and overload points that can be optimized tuning the WC operating point for a particular backhaul fiber transmission distance. Using the optimized settings, sensitivities of  $-30.94$ ,  $-30.17$ , and  $-27.26$  dBm with overloads of  $-9.3$ ,  $-5$ , and  $>-5$  dBm were demonstrated for backhaul transmission distances of 22, 40 and 62 km, respectively.

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## 1. Introduction

Wavelength division multiplexing (WDM) is widely acknowledged as a key technology in the next generation of optical access networks, which will offer higher line-rates, increased numbers of users, and extended reach [1]. Thus, the evolution from Gigabit Passive Optical Network (G-PON) to Next Generation PONs (NG-PONs) requires the integration of WDM in the already deployed G-PON infrastructure. One potential solution introduces a centralized optical processing unit (COPU) to be placed at the intermediate exchange site in a Wavelength Converting Optical Access Network (WCOAN) [2], allowing uncooled, colorless transmitters to be used at the customer's premises so that the access network is scalable and economically affordable to deploy. This exchange node will provide all-optical signal processing, including wavelength conversion, to consolidate the multiple wavelength-drifting burst-mode data streams from each PON segment and convert them to a set of stabilized WDM wavelength channels for transmission over the backhaul fiber, which may consist of dual fibers for the upstream/downstream direction.

In this work, we characterize a device suitable for the aforementioned application by performing a burst-mode BER characterization using a fixed and variable power optical packet transmitter and a PIN-based DC-coupled digital burst-mode receiver [3].

This paper is organized as follows. Section 2 describes the overall architecture of the proposed wavelength converting optical access network and the COPU. The experimental setup and the digital burst-mode receiver used for the characterization of the COPU are described in section 3. Finally, section 4 presents the COPU characterization and the experimental BER results for back-to-back and backhaul transmission distances of 22, 40, and 62 km.

## 2. Proposed wavelength-converting long-reach PON description

The integrated PON with a long-reach dense WDM (DWDM) backhaul wavelength converting access network is shown in Fig. 1. The network can be subdivided into a passive feeder network and an exchange site with backhaul transmission. The passive feeder fiber network connects each customer to the local exchange in identical fashion to traditional PONs with distributed passive optical splitters. The main issues in this section are the high loss associated with the power splitting arrangement, the unlevelled optical burst power due to distance ranging and transmitted power tolerance of the optical network units (ONUs), and the wavelength drift of the ONUs laser sources because of temperature variation for low cost, un-cooled lasers used there.

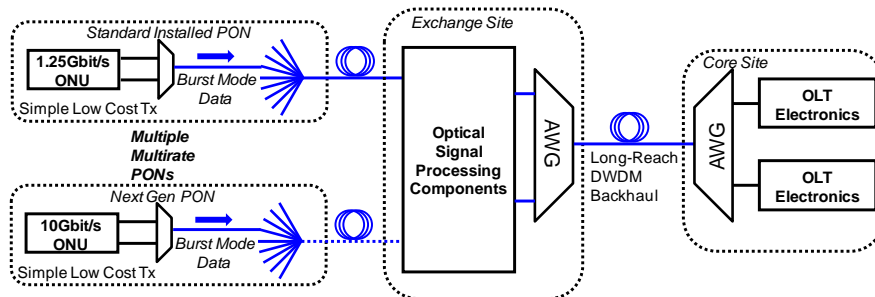


Fig. 1. Architecture of the proposed wavelength-converting long-reach optical access network.

Long-reach WDM access networks typically use active optical amplification at the exchange sites to enhance transmission distance. At the exchange site, shown in Fig. 1, we introduce a centralized optical processing unit (COPU) to consolidate multiple burst-mode data streams with drifting wavelength and unequalled burst powers from each PON segment and convert them to a set of stabilized WDM wavelengths with equalized burst-to-burst power for transmission over the long-reach backhaul fiber.

### 2.1 Centralized Optical Processing Unit (COPU)

The COPU, shown in Fig. 2(a), is composed of an optical power equaliser followed by a wavelength converter (WC), and it is expected to meet three different requirements which are, namely, wavelength conversion, optical power equalization of the optical bursts, and transmission distance enhancement. The wavelength conversion process consolidates multiple Coarse-WDM (CWDM) ONU wavelengths onto a set of fixed DWDM wavelengths for efficient backhaul transmission over a WDM optical link. Also, the unlevelled bursts coming from ONUs at a different distance from the exchange will need to be equalized to reduce the receiver dynamic range requirement at the optical line terminal (OLT). In addition, optical bursts will need regeneration to have a higher extinction ratio and possibly pre-chirping to enable dispersion-tolerant transmission required in the long reach scenario which will increase the backhaul transmission distance over an uncompensated link.

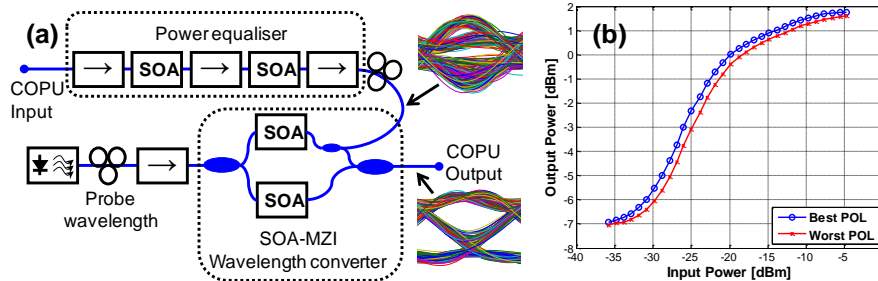


Fig. 2. (a) Centralized optical processing unit diagram, showing the power equaliser, the SOA-MZI wavelength converter, and electrical eye diagrams after the power equaliser and the COPU for  $-15$  dBm input power. (b) COPU output vs. input optical power (CW source).

The principal element in the COPU is the WC, which exploits Cross Phase Modulation (XPM) in a Semiconductor Optical Amplifier Mach-Zehnder Interferometer (SOA-MZI) configuration. This device has previously been proposed for use in WDM enabled core and metro networks [4] and is considered the most effective WC due to its high conversion efficiency, extinction ratio enhancement, and negative chirp characteristics. It can also maintain the extinction ratio of incoming wavelengths that are shorter or longer than the output wavelength within the CWDM band [5]. However, in optical access networks there are additional issues as the incoming wavelength is not stable and the signal is burst-mode and, thus, the optical power among bursts is not constant. Generally, XPM based WCs have a limited input power dynamic range (IPDR) of about 3-4 dB at 10 Gb/s [6]. The IPDR was only 2 dB under normal operating conditions in the prototype used in this work. However, by using a pre-amp SOA to amplify the ONU optical signal power and a second booster SOA operating in the saturated regime to equalize the burst power, the overall input power dynamic range of the SOA-MZI can be enlarged. The power equaliser degrades the extinction ratio and also exhibits patterning effects in dynamic mode, as illustrated in the eye diagrams of Fig. 2(a). These effects are compensated due to the regenerative properties of the nonlinear transfer function of the SOA-MZI WC [7]. However, there are large variations on the output signal extinction ratio and eye shape due to the saturated SOA patterning combined with the nonlinear transfer characteristics of the WC. The static input/output power characteristic of the COPU is shown in Fig. 2(b), measured using a CW light source. For a PON, the approximately 15 dB loss in the splitter limits the COPU input power to the range from  $-15$  dBm to  $-30$  dBm. For this input power range, the output power is from  $+1$  dB to  $-6$  dB, with a static CW polarization dependent gain of 1 dB.

### 3. Experimental setup and digital burst-mode receiver description

Figure 3(a) shows the experimental setup used for the burst-mode characterization. Two ONUs were simulated with two externally modulated distributed feedback (DFB) lasers at

different wavelengths (1553.5 and 1556.3 nm), with an extinction ratio of 14 dB. The COPU probe and pump signals are in a counter-propagation configuration as this generates a better converted signal performance in terms of higher extinction ratio and Q-factor [7]. The probe signal, onto which the upstream traffic is converted, was a CW laser at 1554.7 nm. As this is a proof of concept experimental demonstration only commercially available C-band devices were available in our laboratory. Wavelength conversion from 1.3  $\mu\text{m}$  to 1.5  $\mu\text{m}$  using 1.3  $\mu\text{m}$  SOAs has been previously demonstrated [8]. Thus the results of this experiment which show mapping of 1.5  $\mu\text{m}$  CWDM channels onto a 1.5  $\mu\text{m}$  DWDM grid for backhaul will still hold for the 1.3  $\mu\text{m}$  upstream wavelengths that are typically used in PONs. After the COPU, an optical filter removes out of band noise and simulates the transfer function of the AWG, shown in Fig. 1. Two optical bursts, depicted in Fig. 3(b), were generated from this setup, creating a loud and soft burst each having a 6.5  $\mu\text{s}$  length with a guard time of 204 ns placed between bursts.

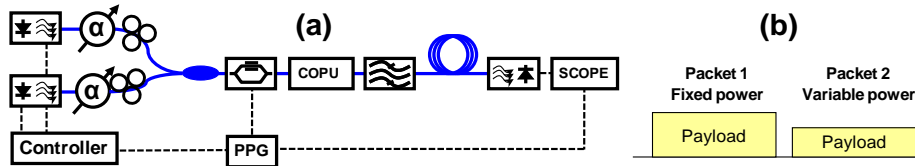


Fig. 3. (a) Experimental setup for the characterization of the COPU. (b) Generated optical bursts.

The burst-mode receiver, shown in Fig. 4, consisted of a digital burst-mode receiver (DBMRx) [3] based on a front-end having a DC-coupled PIN photodiode, electrical filter, and a fast analog-to-digital converter (ADC). The DBMRx is composed of a piecewise-parabolic interpolator controlled by a fractional delay estimator that can be efficiently implemented with a Farrow structure [9]. In this application, this interpolator produces an average of 0.5 dB improvement in terms of sensitivity over a linear interpolator. After the interpolator, the signal is normalized with an estimation of the burst DC-offset and amplitude. Here we use an adaptive threshold slicer [10] to improve burst data recovery (KTh) which includes a baseline-wander filter. We also compare the performance of this with a fixed null threshold slicer (FTh) and an optimum slicer where the optimum threshold is determined with knowledge of the entire burst (OTh). BER measurements up to  $10^{-6}$  were carried out by error counting using offline processing. This allows for a good confidence interval measurement around the BER forward error correction (FEC) limit of  $10^{-3}$ , which is required by the 10G-EPON standard.

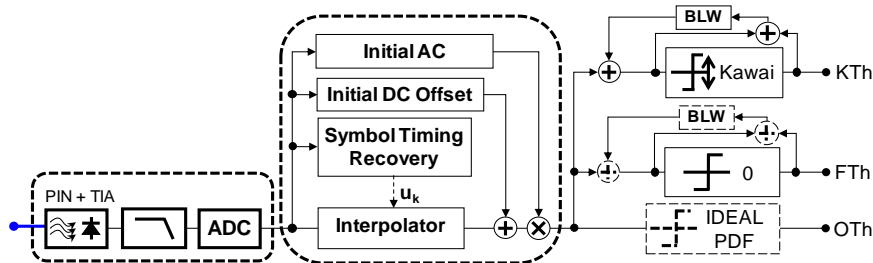


Fig. 4. Diagram of the digital burst-mode receiver used in the characterization of the COPU.

## 4. Results and discussion

### 4.1 COPU optimization procedure

The performance of the prototype COPU used in this work with respect to the input power range can be tuned by adjusting the WC bias point. The polarization controller between the probe laser and the COPU was optimized in order to maximize the WC extinction ratio. Since the CW probe is physically located close to the SOA-MZI or even packaged together, once

the polarization for the probe is optimized it is not expected to change. However, in a real system the polarization of the burst coming from the ONU is random. The SOAs used in the equalization stage are polarization insensitive but the SOAs inside this prototype SOA-MZI device had a strong polarization dependent gain (PDG). The PDG changes the signal power in one arm of the SOA-MZI, which affects the bias point of the WC and can result in an up to 2.5 dB dynamic polarization penalty for the received BER sensitivity. It is expected that a production grade SOA-MZI device will be used in the real system, which will have an optimized SOA active region and is polarization insensitive [11]. Therefore, the bias point of a polarization insensitive SOA-MZI device will not be affected by the random polarization of the ONU bursts.

The following procedure was used to adjust the ONU polarization, i.e., the WC bias point, to overcome the polarization penalty of this prototype device. Two bursts of  $-15$  (loud) and  $-25$  dBm (soft) were generated and then three COPU optimization cases, named A, B, and C, were chosen. These cases are illustrated in Fig. 5 for a backhaul transmission distance of 22 km, where the soft burst eye was superimposed on the loud burst eye. The loud burst eye exhibits a nonlinear distortion due to patterning-generated additional optical power before the SOA-MZI sinusoidal transfer function, which contrasts with the characterization of Fig. 2(b) where no eye overload is noticeable in static CW mode. In case A, the optical eye diagram of the loud and soft bursts was equalized as much as allowed. Ideally, this would be the case for the real system with a polarization insensitive SOA-MZI device. Case C is the opposite and so the amplitude of the loud burst is maximized and the power of the soft burst is minimized. Case B is a compromise between cases A and C.

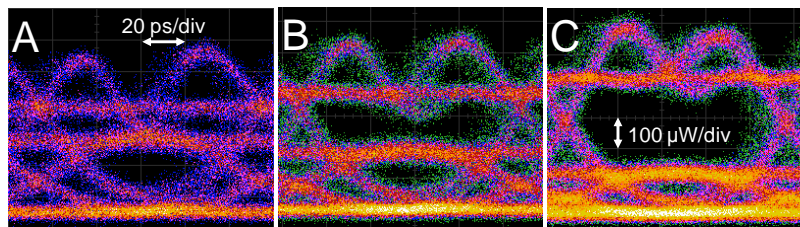


Fig. 5. COPU output signal eye diagrams after 22 km of fiber for (a) polarization case A, (b) polarization case B, and (c) polarization case C.

#### 4.2 COPU BER characterization

The four plots in Fig. 6 show the soft burst BER performance in burst-mode operation for COPU optimization cases A and B. Case C, which follows the trend of increasing the overload point and reducing the sensitivity, is not plotted here for clarity. In these measurements, the optical power of the loud burst was fixed at  $-15$  dBm in order to simulate the 32-way splitter loss, while the power of the soft burst was swept from  $-5$  dBm to  $-35$  dBm in 1 dB steps. The back-to-back (BB) curve in Fig. 6 indicates the DBMRx sensitivity in burst-mode operation and was measured by connecting the burst-mode transmitter straight into the DBMRx. In order to avoid quantization clipping and consequently nonlinearities at the digital receiver, the quantiser range of the digital receiver and the optical attenuation was configured for every transmission distance to keep the maximum received electrical signal within quantization limits. Consequently, a 4 dB optical attenuator was used for BB.

The sensitivity of the digital receiver is maximal for the 0 km case and diminishes with transmission distance due to fiber losses and dispersion. On the contrary, the overshoot of the receiver is worse for the 0 km case and improves with the transmission distance. The SOA-MZI device operating in non-inverting mode has the benefit of generating negative chirp. The pre-chirped converted signal reduces the impact of dispersion and so the results show that the overshoot improves when fiber distance increases from 0 km to 22 km. In addition, no significant benefit is observed between the variable-threshold slicer and the fixed threshold

slicer, which leads to some DSP resources savings compared to the work in [12]. There is a tradeoff between receiver sensitivity and overload, which can be observed in Fig. 6(b) (22 km transmission), where a reduction of 1 dB in sensitivity leads to a 5 dB improvement in overload switching from COPU optimization case A to B.

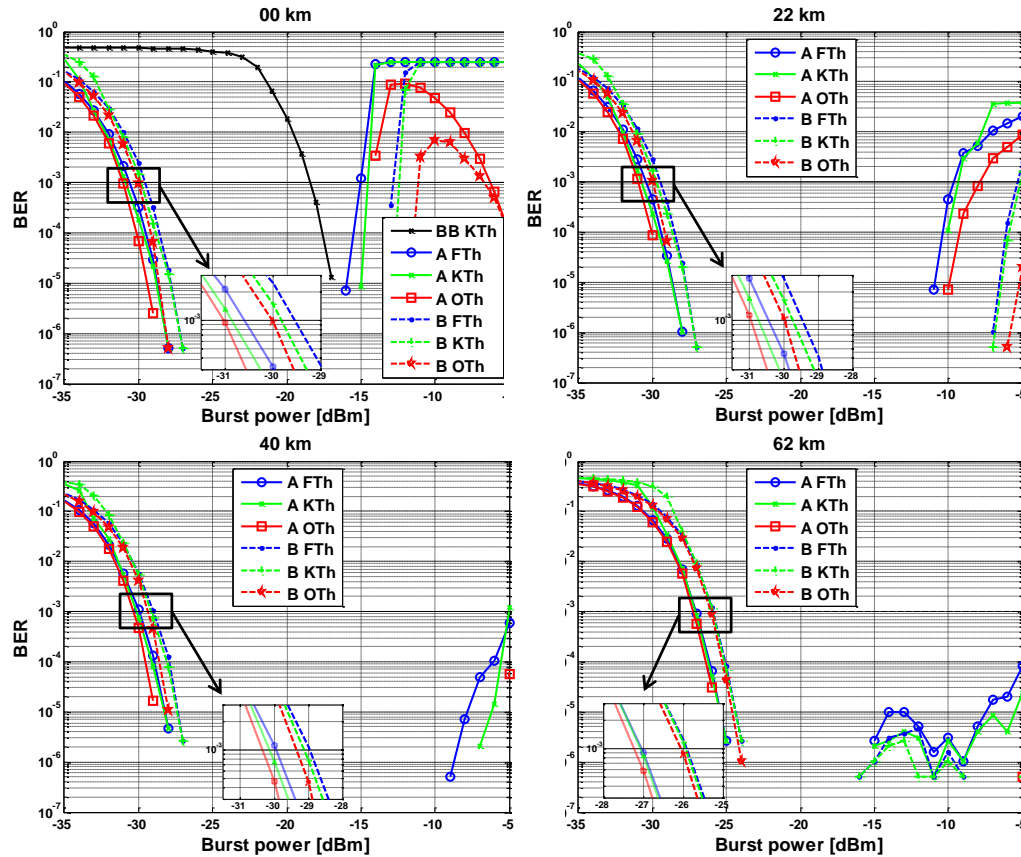


Fig. 6. Experimental BER characterization of the COPU for (FTh) fixed null threshold slicer, (KTh) Kawai variable-threshold slicer, and (OTh) optimum slicer for cases A and B for backhaul distances of (a) 00 km (COPU and no fiber), (b) 22 km, (c) 40 km, and (d) 62 km. The black line represent the back-to-back (neither COPU nor backhaul fiber) case.

## 5. Conclusions

In this paper, we have characterized a centralized optical processing unit for integrating multiple 10 Gb/s CWDM PONs segments into a long-reach DWDM backhaul. The COPU consists of a power equaliser combined with a WC and is shown to provide both burst equalization and wavelength conversion.

It was shown that there is a tradeoff between the maximum sensitivity of the receiver and the overload point which can be optimized by varying the operating point of the WC. 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  $-30.94$ ,  $-30.17$ , and  $-27.26$  dBm with overload points of  $-9.3$ ,  $-5$ , and  $>-5$  dBm were found, respectively. Also, in this application a fixed null threshold slicer performs similarly to a more complex variable-threshold scheme, which could lead to significant receiver DSP resource savings.

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