A novel burst-mode all-optical wavelength converter based on gain-clamping structure

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Abstract. A novel gain-clamped wavelength converter (GCWC) is proposed to make the hybrid TDM-WDM PON architecture based on wavelength conversion feasible, and its operation principle is also demonstrated. The power budget of this network is measured to identify the architecture can support 4096 users who share 40 Gbit/s accessing capacity on a single trunk fiber. And optical power equalization functionality and burst transparency characteristic of GCWC is experimentally evaluated, and the results show that the GCWC makes burst signals from different transmitters with up to 5 dB dynamic range equalized and is transparency for burst signals.

1. Introduction
Passive optical network (PON) is one of the most promising optical access network architectures in terms of cost-effectiveness. Time division multiplexing (TDM) PON offers low per-subscriber cost by sharing a single wavelength channel with multiple subscribers. However, it inevitably sacrifices per-subscriber bandwidth. The increasing demand for new high bandwidth services, such as VoIP, HDTV and cloud computing, will drive the enhancement of its cost-effective features. Wavelength division multiplexing (WDM) PON can provide large transmission capacity, network security and flexibility. However, the issue of the cost-effective optical source and arrayed waveguide grating (AWG) impedes a commercial WDM-PON deployed.

Recently, there has been increasing interest in hybrid PON (HPON) architecture that aggregates a number of TDM-PONs by WDM to share the same trunk fiber, since the costs is reduced by sharing the deployed infrastructure fiber among more customers\textsuperscript{1-3}. Obviously, HPON is suitable for near future deployment in pragmatic migration from current TDM-PON to WDM-PON. All-optical wavelength converter (AOWC), as one of the key technologies employed in several reported HPON architectures, converts the various wavelengths of ONU transmitters to a stable wavelength allocated for upstream. In consequence, the colorless ONUs is feasible in the AOWC based HPON system, resulting in a reduced costs of operation, administration and maintenance. However, the reported AOWC scheme based on semiconductor optical amplifier (SOA) was complex in structure and the performance was poor for wavelength upconversion\textsuperscript{4}.

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In this paper, we propose a novel semiconductor all-optical wavelength converter based on gain-clamping structure to ensure the hybrid TDM-WDM PON architecture feasible, and measure the power budget of the HPON. Then, the power equalization functionality and burst transparency characteristic of GCWC is experimentally investigated.

2. Network architecture and operation principle

Figure 1 illustrates the architecture of the proposed hybrid TDM-WDM PON. The layout is divided into three locations, namely: central office (CO), remote node (RN) and colorless ONU. The fiber between CO and RN, referred to as the optical trunk line (OTL), is 40km. The fiber between RN and ONUs, referred to as the optical distribution network (ODN) fiber, is 20 km. A single fiber scheme is employed for the TDM-PONs, which feature a split of 256, 20km reach. Each TDM-PON is assigned an upstream (US) and a downstream (DS) wavelength, and both US and DS bands use 200GHz channel spacing. A guard band of 20nm is kept between the US and DS band, enabling the use of low-cost red/blue filters in the RN and ONU to separate US and DS channels. Reach extender box for each TDM-PON, consisting of two erbium-doped optical fiber amplifiers (EDFA) and a specific wavelength GCWC, is located at the RN to extend fiber length and splitting ratio.

Figure 2. ONU colorless concept and the structure of GCWC.
The ONUs employed in the proposed HPON should be colorless (in other words, no ONU is wavelength specific) to decrease the costs, since mass production becomes possible with just one specification. However, WDM utilized in the architecture requires ONU wavelength strictly defined to ensure that is can pass through each optical filter. Many colorless proposals have been reported\cite{5}. The concept of our system is shown in figure 2. We proposed a novel semiconductor optical wavelength converter based on gain-clamping structure, which consists of a tilted-waveguide SOA chip with anti-reflective coatings on facets and a pair of fiber Bragg gratings coupled to the SOA chip by conical fiber lenses. The optical spectrum of ONUs employed in the proposed HPON system, shown in the figure 2, is monitored by an optical spectrum analyzer [(OSA) Agilent 8614B]. The GCWC converts the wavelengths of the colorless ONUs to a stable wavelength with a 0.2nm linewidth@-20dB, which is strictly defined to ensure that is can pass through each optical filter of the WDM. Hence, the colorless ONU is feasible.

When a data signal is injected into the proposed GCWC, the internal laser power will vary inversely to the input signal power in order to obtain a constant cavity gain. When a “1” pulse is injected, the carriers are depleted and the gain of the internal laser decreases; therefore, the internal laser outputs a “0” pulse. For a “0” pulse, the gain is not affected; therefore, the internal laser outputs a “1” pulse. So, inverted wavelength conversion is achieved. Benefitting from the gain-clamped structure, GCWC also acts as an optical power equalizer\cite{6}.

3. Experimental demonstration and discussion
First, to evaluate available power budget in the HPON system utilizing the proposed GCWC, we measured the bit error rate (BER) performances of 2.5Gbps transceivers in the OTL between the CO and RN, and in the ODN between the RN and ONUs as a function of the inserted loss, respectively. From figure 3 and figure 4, we found that a power budget of more than 18.5 and 32.5 dB were achieved in the trunk span and ODN, respectively. In addition, we evaluated the dispersion penalties induced by 40km standard single mode fiber (SSMF) in the trunk span and 20km SSMF in the ODN. From figure 3, it was found that a dispersion penalty of 1.7 dB for 40km in the trunk, 1 dB for 20 km in the ODN and 2.0 dB for 60km was induced. From figure 4, it was found that no dispersion penalty for 20km in the ODN, a dispersion penalty of 1.8 dB for 40 km in the trunk and 60km in total was induced. These results indicated that by adopting the proposed hybrid TDM-WDM reach extender, a power budget in trunk span and ODN can be extended by more than 16.5 dB and 30.5 dB, respectively. The power budget in ODN ensure the 20 km ODN reach (4 dB) and 1:256 split ratio (24 dB) feasible, and the power budget in trunk span ensure the 40 km trunk fiber (8 dB) and 16 channels (WDM insert loss = 6 dB) feasible.

Figure 3. OTL budget performance for upstream.

Figure 4. ODN budget performance for upstream.
Benefitting from the gain-clamped structure, GCWC also acts as an optical power equalizer to solve the near-far problem, which means that the burst-mode receiver used in this HPON system could be less complex in electronic circuits than the formerly reported one. To investigate the power equalization ability of GCWC, we monitored the input and output of GCWC through a communications signal analyzer [(CSA) Tektronix 7404B]. The waveforms obtained at input and output of the GCWC for 5dB power differences between burst frames are shown in figure 5. The results show that the GCWC could equalize burst signals with in excess of 5dB dynamic range. Figure 5 also shows that the time length of the burst frames and the time interval between them keep invariable, not as the optical electrical optical scheme\(^7\). The results show that the clock data recovery signals in the burst frames is not consumed and GCWC realized the transparent wavelength conversion for burst data.

![Figure 5. Waveforms obtained at the input (a) and output (b) of GCWC.](image)

4. **Conclusion**
A novel semiconductor all-optical wavelength converter based on gain-clamping structure was proposed to meet the requirements of a hybrid TDM-WDM PON architecture, which has been adopted by ITU-T Rec. G.984.6 Amd.1\(^8\).

We demonstrated that the HPON architecture utilizing the proposed GCWC is feasible and offers an extended power budget of in excess of 47dB, which reveals that the system can potentially support up to 16 TDM-PONs on a single fiber and accommodate 4096 users at 40Gbit/s in total. The power equalization functionality with at least 5dB dynamic range and the burst transparency characteristic of GCWC was experimentally confirmed.

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