Migrating Legacy PON Equipment towards Colorless ONU through Hybrid Integrated SOI All-Optical λ-Converter

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Abstract: We present an ONU featuring a “colorless” DML enabled by a wavelength converter integrated on a 4μm silicon-on-insulator substrate. The photonic chip employs a hybrid integrated SOA and delay-interferometers and supports operation beyond 10Gb/s.
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1. Introduction

Optical access has undoubtly brought broadband to the user and is about to introduce novel services such as 3DTV. With its standardization, mature equipment for E/GPON and, more recently, 10G-EPON/XG-PON has been released to the market [1]. However, due to the colored equipment applied in nowadays FTTH communication equipment, a smooth upgrade towards NG-PON2 is prohibited. Although the use of WDM in future access networks has fuelled the development of low-cost tunable lasers [2], the possibility of recycling colored customer premises equipment for colorless hybrid WDM/XDM-PON environments has not been investigated yet since low-complexity and integrable wavelength converters have been missing in the rather small toolbox of access networks. However, the recent advances in silicon-on-insulator (SOI) photonic technology have enabled the deployment of fully integrated circuitry for optical telecommunication. The new technology trend focuses on the design, fabrication and dense integration of passive/active components on-chip for compactness, flexibility and high data rates [3]. These properties can be attractive as well in WDM-PONs, where simplicity, energy-efficiency and low capital expenditures are required. So far, hybrid integration on silicon substrates has produced a variety of active components including micro-disk lasers and photodetectors [4-6]. A new waveguide technology is now being attempted for the hybridization of mature, pre-fabricated III-V components on SOI motherboards using microsolder bumps. This type of hybrid integration has recently produced a high-speed all-optical wavelength converter (AOWC) integrated on a 4 μm SOI rib substrate [7]. Due to its small footprint, low power consumption and wavelength selective properties, the device allows to introduce a wavelength transparent upstream with colored optical sources at the ONU.

In this paper we demonstrate the implementation and performance evaluation of a colorless ONU for full-duplex transmission at 10Gb/s in a WDM-PON, based on the liaison of a directly modulated laser (DML) and a hybrid AOWC. The photonic chip incorporates a 1.25 mm prefabricated non-linear SOA mounted on the SOI board using gold-tin bumps as small as 14 μm. Optical filtering is realized by two cascaded delay interferometers (DIs) integrated on the SOI board using 2×2 multi-mode interference couplers. Full free spectral range (FSR) tuning of the DIs is accomplished by two independently tuned on-chip thermal heaters

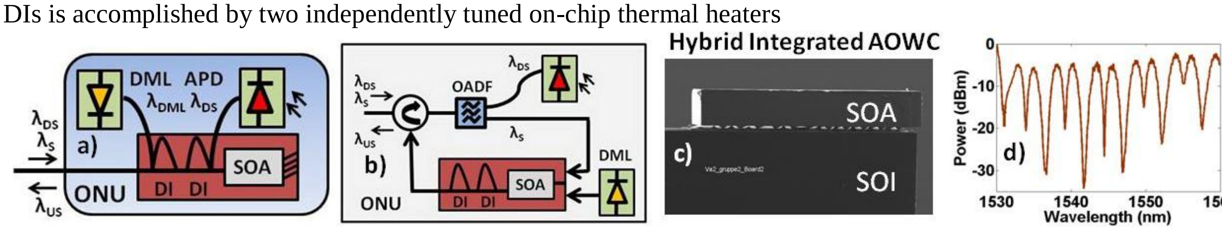


Figure 1: a) proposed ONU scheme, b) proof-of-principle ONU, c) SEM image of fabricated AOWC, d) spectral DI response for ASE seed

2. Concept and Experimental Setup

Fig. 1a depicts the proposed ONU design to introduce colourless operation in a WDM/XDM PON. It is comprised of three main blocks: a conventional DML (or EML) -based upstream transmitter, a hybrid integrated all-optical wavelength converter and the downstream receiver. The AOWC features two basic components: a reflective SOA

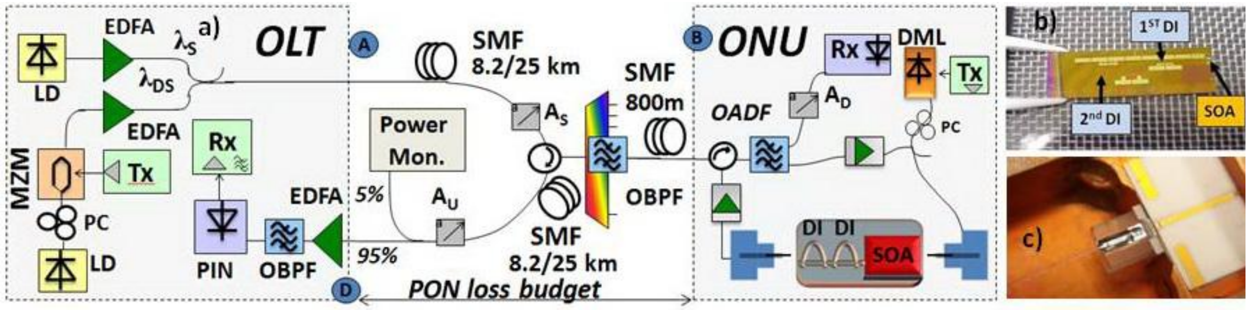


Figure 2: a) Experimental proof-of-concept setup, b) fabricated AOWC, c) DML

and the SOI integration board. The SOA is used as non-linear element for wavelength conversion by means of cross gain modulation (XGM). The SOI integration board performs add-on wavelength processing with two cascaded delay interferometers. The first one is utilized as periodic WDM filter, whereas the second one serves as an additional filter for obtaining spectral responses with higher outband suppresion. At the same time, the functionality for the downstream drop can be incorporated. The concept was validated with a proof-of-principle ONU having a two-port AOWC (Fig. 1b), since no reflective SOA was available. Both SOA and SOI functionalities are combined in the same platform using AuSn bump sputtering and flip-chip integration techniques. Fig. 1c shows the active SOA chip flip-chip mounted on the SOI substrate with good mechnical stability. Fig. 1d shows the recorded DI spectral characteristics after using ASE seed into the hybrid integrated SOA. The FSR of the DIs has been measured to be 6 and 3nm, respectively, and with proper wavelength tuning a spectral notch of ~30dB has been observed.

The principle operation of the ONU relies on the following procedure. The optical line terminal distributes together with the downstream signal (λ_{DS}) a seed wavelength λ_S. These two wavelengths are separated at the ONU with an opical add/drop filter (OADF), which is in its simplest form a Red/Blue filter but can be functional integrated in the DI cascade. While the downstream is detected, the seed wavelength λ_S is injected together with the upstream data from the DML into the hybrid AOWC. Due to XGM, the upstream data is imprinted onto the seed wavelength. Thanks to the 60 nm wide 3-dB optical gain bandwidth of the SOA, wavelength conversion can be performed for the whole spectrum of the WDM-PON. This means that DMLs with higher modulation bandwidth than traditional RSOA-based upstream transmitters can be used at the ONU, while inventory and stockpiling problems are avoided at the same time as a single DML wavelength λ_{DML} can be used for all ONUs in the PON. The consecutive integrated DIs assist with three basic processes: a) suppression of the DML (pump) signal after the wavelength conversion, b) maintaining colourless operation due to their comb-like spectral profile and c) optional offset chirp filtering for supporting ultra-fast data operation. The latter is enabled by the simultaneous cross-phase modulation during the wavelength conversion progress [8] and provides an upgrade path for the upstream data rate beyond 10 Gb/s, e.g. in combination with chirp-managed DMLs [9]. The wavelength-translated upstream signal is then received at the OLT on its designated wavelength λ_S.

Fig. 2 illustrates the experimental setup. The 10 Gb/s downstream is transmitted from the OLT at λ_{DS} = 1543.67 nm together with the seed wavelength λ_S = 1550.3 nm for the upstream transmission. Both wavelengths are launched into the WDM-PON with 10 dBm/λ. The DML at the ONU injects the 10 Gb/s upstream into the AOWC at λ_{DML} = 1547.36 nm. The electro-optical modulation bandwidth of the uncooled DML was 6.5 GHz and the bias was as low as 35 mA. Though this wavelength map does not fit to any access standard due to the unavailability of 10G-EPON or XG-PON equipment, it proofs the principle sufficiently as it relies on similar conditions: a dedicated Blue waveband for the downstream and, as will be shown shortly, WDM operation at the Red upstream waveband. Note that in case of 10G access standards the SOA gain spectrum would have to be centered in the O-band at 1310 nm. The seed wavelength λ_S and the output of the DML are launched through a lensed fiber into the hybrid all-optical wavelength converter with power levels of 12dBm and 9dBm respectively. The rather high power values were required to compensate for the overall fiber-to-fiber loss of the chip, measured to be ~18dB. The main reason for this loss was attributed to the x-axis lateral misalignment between the SOA facet and the SOI waveguide during the flip-chip fabrication process. EDFAs were included in the ONU for this purpose, however, by replacing the SOA with a high-gain RSOA [10] as proposed in Fig. 1a and improving the coupling efficiency at the same time, these EDFAs can be avoided.

3. Results and Discussion

The performance of the proposed ONU configuration was evaluated in terms of bit-error-ratio (BER) measurements using variable attenuators (A_D, A_U) in front of the downstream and upstream receiver. Fig. 3a depicts the back-to-back (B2B) BER curves. The downstream reception does not impose any limitation due to its high compatible loss

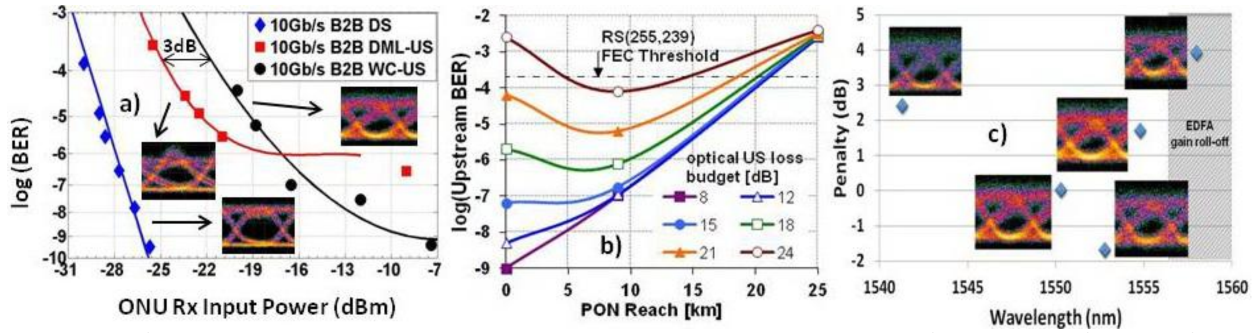
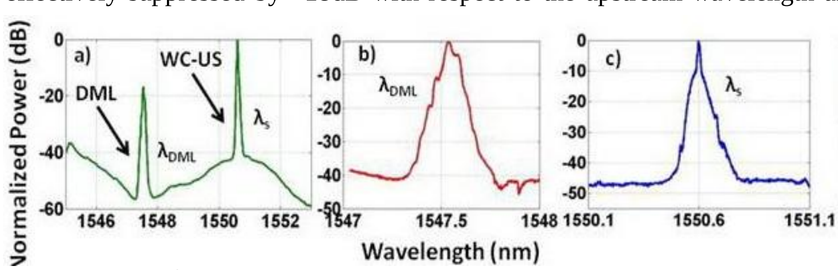


Figure 3: BER for a) B2B downstream and upstream with DML and DML+WC, b) compatible PON reach for the upstream after AOWC for various loss budgets, and c) colorless operation of the AOWC showing the penalty with respect to 1550.3 nm.

budget beyond 30 dB, neither it requires to use of forward error correction (FEC) at the cost-sensitive ONU. In case of the upstream, direct transmission with the DML at λ_{DML} without AOWC but with the same launched power from the ONU, an error-floor at 10^{-6} was observed and is attributed to the bandwidth limitations and the residual ripple of 2 dB in the e/o response of the device (see patterning in eye inset of Fig. 3a). After the wavelength conversion process, which introduces also regenerative properties as the saturated SOA acts as power equalizer [11], the upstream signal shows better performance with low error-floor. Fig. 3b shows the upstream performance exploiting the AOWC after transmission over SMF in the drop and feeder segments of the WDM-PON. Upstream loss budgets of up to 20 dB are compatible with a reach of ~18 km. Fig. 3c demonstrates the colorless operation of the ONU using different seed wavelengths λ_S transmitted by the OLT. The power penalties with respect to the original 1550.3 nm wavelength are ranging +/-2dB. This is mainly attributed to the SOA gain profile as well as to the non-uniform spectral response of the cascaded DIs. The extra-ordinary high penalty observed for 1557 nm operation derives from the limited operational area of the EDFAs used in the setup. Considering these penalties for the upstream transmission, the overall PON loss budget is still limited by the seed loss budget for the ONU to 18 dB.

Fig. 4a depicts the spectrum after the hybrid AOWC. It is obvious that the pump signal (i.e. DML) has been imprinted on the seed at λ_S. In addition, due to the DI periodic filter responses, the DML carrier component has been effectively suppressed by ~18dB with respect to the upstream wavelength and is further suppressed by the WDM



Stream / Seed	Tx Power [dBm]	Rx Sens. / ONU input [dBm]	Loss Budget [dB]
Ds	10	-29.8	39.8
Us	0	-23.6 ... -19.6	23.6 ... 19.6
CW	10	-8	18
Compatible loss budget [dB]:			18

Figure 4: Spectra of a) AOWC output, b) upstream signal, and c) DML output. The table summarizes the compatible B2B loss budgets.

demultiplexer in the fiber plant. Fig. 4b and 4c show the spectra of the DML output and the transmitted upstream.

4. Conclusions

We have presented an upgrade from colored to colorless ONUs using a hybrid all-optical wavelength converter on a silicon-on-insulator substrate. The photonic chip performs wavelength conversion using a flip-chip mounted SOA and two concatenated delay interferometers that provide also the possibility of additional chirp filtering.

5. References

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