Colorless ONU With Discolored Source and Hybrid SOI Integrated Wavelength Converter

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***Abstract*— We present a novel optical network unit (ONU) featuring a "colorless" directly modulated laser (DML) enabled by a hybridly integrated all-optical wavelength converter (AOWC), supporting operation beyond 10 Gb/s. It incorporates a semiconductor optical amplifier (SOA) for wavelength conversion and two cascaded delay interferometers (DIs) for spectral processing. The ONU was proven at full duplex 10-Gb/s data rate in a WDM passive optical network.**

***Index Terms*— Fiber-to-the-home (FTTH), optical access, optical communication terminals, wavelength conversion (WC).**

I. Introduction

COLORLESS WDM has been considered a key technology for enabling broadband services to the user. So far, colored equipment applied in present FTTH communication equipment has prohibited a smooth upgrade towards NG-PON2. On the contrary, WDM-PONs employing wavelength independent ONUs are now being investigated as network topologies with simple administration, maintenance requirements and low operational expenses [1]. The overall implementation relies on "colorless" concepts, in which wavelength channel generation and control are kept in the central office, while wavelength agnostic remote US modulation is applied at customer premises. Until now, one of the first demonstrations of colorless ONUs has been implemented with a reflective SOA (RSOA), which offers data rates up to 10 Gb/s, but with a trade-off between the gain and bandwidth that limits its operational speed. An alternative path is to recycle colored customer equipment for colorless WDM/XDM-PON environments exploiting WC procedures.

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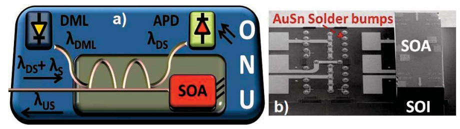

Fig. 1. (a) Colorless ONU. (b) SEM image of flip-chip bonded SOA.

However, the absence of compact, energy efficient and bandwidth transparent devices sets major restrictions for large scale implementation in access networks. In this context, silicon-on-insulator technology (SOI) has recently enabled fully-integrated photonic circuits for a range of applications in data communications. Current research efforts are now focused on the hybridization of mature, pre-fabricated III-V components on micrometer SOI motherboards using micro-solder bumps and flip-chip mounting processes. This type of procedure has recently produced a high-speed hybridly integrated AOWC on a 4 μm SOI rib substrate [2]. Considering its small footprint, low power consumption and wavelength selective properties, upstream (US) wavelength transparency with "colored" source equipment at the ONU is ensured, imposing energy-efficiency and low capital expenditures.

In this letter we demonstrate a novel colorless ONU design incorporating a DML together with a hybrid integrated AOWC, verifying its operation at 10 Gb/s in a WDM-PON.

II. Erasing the Color of the DML

The fundamental building blocks of the proposed ONU (Fig. 1) are a downstream (DS) receiver (Rx), a conventional DML-based US transmitter (Tx) and a hybridly integrated AOWC. Its operational cornerstone is the AOWC, which imprints the colored US signal at λ_{DML} onto the remote seed λ_S transmitted by the OLT. Treating the ONU as a "black box", it appears to be identical as the one featuring a reflective modulator. However, higher modulation bandwidth DMLs at the ONU replace traditional bandwidth limited RSOA-based US Tx. In addition, inventory and stockpiling problems are avoided since a single DML wavelength can be used for all ONUs in the PON. The AOWC features a RSOA and two cascaded DIs, integrated at the same SOI board. The SOA is used as a non-linear element for cross gain modulation (XGM)-based WC, while the DIs employ add-on wavelength processing, which allows: a) suppression of λ_{DML} after the WC, b) ONU colorless operation due to their comb-like spectral profile and c) optional chirp filtering for supporting ultra-fast data operation [7]. The last is empowered by the simultaneous cross-phase modulation during the WC progress, which provides an US upgrade path beyond 10Gb/s. More specifically, the first DI acts as periodic WDM filter to

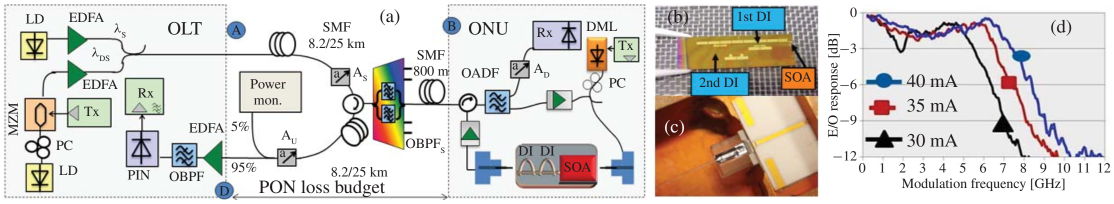

Fig. 2. (a) Experimental proof-of-concept setup. (b) AOWC photonic chip. (c) DML. (d) DML electro-optical (e/o) response for different bias currents.

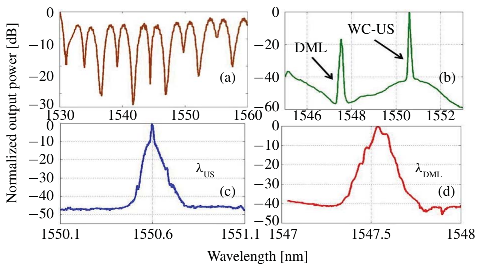

Fig. 3. Spectra of (a) cascaded DI response in case of ASE injection, (b) output of AOWC, (c) WC US, and (d) DML output.

interleave the US at λ_{DML} with the seed at λ_S, whereas the second one acts as an additional filter for obtaining spectral responses with higher outband suppression allowing to drop the DS at the same time.

Since no RSOA was available, the concept was validated with a proof-of-principle ONU, having a two-port hybrid integrated AOWC. The device employs a prefabricated 1.25mm non linear SOA and two cascaded DIs (Fig. 2b). A buried heterostructure with p-n current blocking layers is flip-chip adapted on the SOI motherboard with 14 μm AuSn bumps. Laterally tapered in/output waveguides act as spot-size converters. For proper horizontal and vertical optical adjustment, alignment marks and dry etched trenches are implemented as counterparts to the SOI board stand-offs. The motherboard incorporates an integration zone forming a landing site for the SOA. The SOA mounting on the SOI substrate is being performed by a high accuracy flip-chip bonder (1 μm precision) taking over the positioning against the stand-offs and the thermal cycling for bump reflow soldering. The AOWC had a fiber-to-fiber loss of ~20dB due to the 3 μm x-axis offset misalignment between the SOA facet and the SOI waveguide, which can be further reduced after a series of flip-chip attempts and high-level optimization towards to a placement accuracy down to submicron level. The cascaded DIs have a Free Spectral Range (FSR) of 5.6nm and 2.52nm and their optional full FSR tuning is accomplished by two independently tuned on-chip thermal heaters.

III. Experimental Validation in WDM-PON

The proposed ONU was proven in a WDM-PON setup (Fig. 2a) at 10Gb/s full-duplex transmission. The OLT distributes together with the 10Gb/s modulated DS signal at $\lambda_{DS} = 1543.67$nm an unmodulated seed wavelength at $\lambda_S = 1550.3$nm with 13dBm total power and an optical signal-to-noise-ratio (OSNR) of 47dB (λ_S) and 42.9dB (λ_{DS}) respectively. The optical distribution network was composed by a dual feeder fiber link with lengths of 8.2 or 24.2km of standard single mode fiber (SSMF) and a short drop fiber of 800m. The PON wavelength distributing element was considered to be a cyclic AWG and was emulated by two tunable 1nm optical bandpass filters and two 3dB couplers. The loss budget, defined between the OLT and the ONU, was fixed to 20dB for both transmission directions by attenuators (A_S, A_U). At the ONU, a Red/Blue optical add/drop filter (OADF), that can be in principle functionally integrated in the DI cascade, separates λ_{DS} and λ_S. The former is detected with a PIN+TIA combination. The ONU-Tx employs a packaged DML with a bandwidth of 6.7GHz when biased at 35mA (Fig. 2d), emitting at $\lambda_{DML} = 1547.36$ nm. Then, both the seed at λ_S and the US data at λ_{DML} were combined and co-injected into the AOWC. The high chip losses were compensated by two EDFAs before and after the AOWC. The ONU output power and OSNR were 1dBm and 34.6dB, respectively. Due to the 60nm 3-dB bandwidth of the SOA at its bias current of 140mA, WC can be accomplished for the whole WDM-PON spectrum. Furthermore, the fast SOA recovery time (Δt_{10-90}) of ~30ps enables WC at high data rates beyond current access standards. The wavelength-translated US is then received at the OLT on its designated wavelength λ_S by an EDFA+PIN-based receiver.

IV. Results and Discussion

The normalized spectra of the periodic response of the DIs, the AOWC output, the WC-US (λ_S) and the DML output (λ_{DML}) are presented at Fig. 3(a-d). As can be noticed, the DIs biasing was not performed, since both λ_S and λ_{DML} were adjusted to fit with a peak and a notch of the DIs. For the bit-error ratio (BER) measurements (Fig. 4a-f), variable attenuators (A_D, A_U) were placed in front of the DS and US Rx. Figure 4a) depicts the B2B BER curves of the DML-US for different data-rates. Error floors (EF) at 3.10^{-7} and 2.10^{-4} are observed for bit-rates of 10 and 12Gb/s, respectively, due to the bandwidth limitation of the DML (Fig. 2c). A lower rate of 7.5Gb/s improves the sensitivity by 6dB at the Reed Solomon (255, 239) forward error correction (FEC) threshold. Figure 4b shows the transmission results of the direct DML-US over different feeder lengths for a fixed data rate of 10 Gb/s. A low BER of 10^{-10} was achieved over 9km, improving the power margin by 4.7dB at the FEC level with respect to the B2B case. As explained in [3], a slight offset filtering at OLT-Rx and the broadening of the chirped DML pulses, caused by the dispersion, leads to a significant overshoot reduction at the their trailing edges. Hence, the overall DML performance is improved. Increasing the PON reach at 25km, the pulse dispersion dominates and an EF is noted at a level of 2.3 10^{-3}.

Figure 4c) depicts the BER curves referring to the WC-US. Unlike the EF of the 10G/s B2B DML-US, a lower

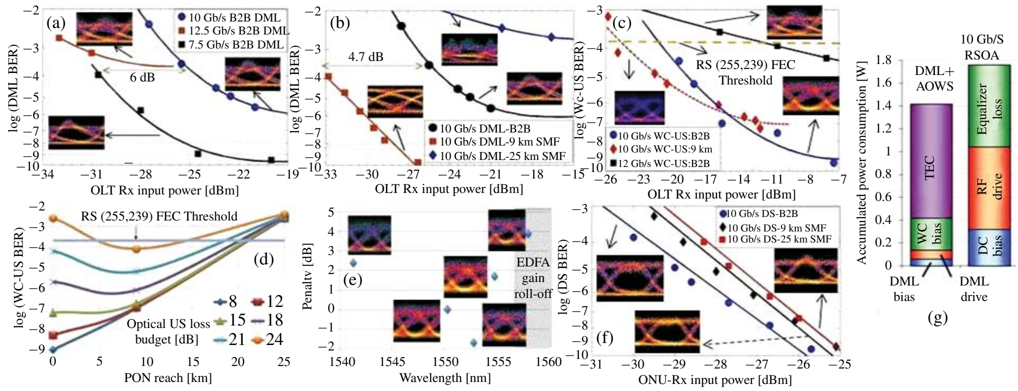

Fig. 4. (a) and (b) BER for DML-US in (a) B2B and different rates and (b) transmission at 10 Gb/s. (c)–(e) BER for WC-US at (c) different rates, (d) different PON reach, and (e) for colorless operation. (f) BER for DS at 10 Gb/s. (g) Power consumption comparison for the AOWC- and a RSOA-based ONU.

BER of 4.10^{-10} can be accomplished in case of the WC. This is mainly attributed at the gain dynamics of the SOA, when it is operated at deep saturation. The injected pulses from DML lead to carrier depletion and, consequently, overshoots at the trailing bit edges are gain suppressed. Thus, the SOA acts as a power limiter and pulse-shaper circuit [4]. Therefore, the XGM-based WC to a co-propagating seed signal is not affected by transient amplitude fluctuations as it is the case for the DML without WC, due to the 2R regenerative behavior of the AOWC. Also, by further increasing the DML data rate to 12Gb/s, the WC-US shows a comparably decreased EF at 5.10^{-5}, at which a penalized reception is still possible. At Fig. 4d) the US performance exploiting the AOWC is shown for different PON reach as function of the loss budget. US loss budgets of up to the targeted 20dB are compatible with a reach of ~18km. As prementioned, the curves' dip noticed at ~9km stems from the offset filtering performed at the OLT-Rx.

The colorless ONU operation was validated under different OLT seed wavelengths λ_S, which were centered at the periodic peaks of the cascaded DI response. By maintaining the B2B BER curve for $\lambda_S = 1550.3$nm as reference, indicant B2B BER points for four additional seed wavelengths were acquired. As indicated in Fig. 4e), the power penalties with respect to the original 1550.3nm wavelength are ranging $+/-2$dB. This is mainly attributed to the SOA gain profile as well as to the non-uniform spectral response of the DIs. The extra-ordinary high penalty observed for 1557nm operation derives from the limited operational area of the EDFAs and the degraded WC efficiency occurring for far detuned wavelengths. Figure 4f) presents the BER performance of the DS. Transmission at 10 Gb/s over 9 and 25km shows a penalty of <1dB at a BER of 10^{-10} with respect to the B2B case. A budget beyond 30dB is suitable for the DS, leaving a power margin of ~15dB without FEC. Table I summarizes the compatible PON loss budgets in case of FEC at the Rx. As the smallest, the seed loss budget imposes a limitation to 18dB at the overall budget.

Finally, the power consumption of the proposed AOWC-based ONU and an equivalent 10Gb/s RSOA-based ONU [5] was investigated (Fig. 4g). In a direct comparison between the modulators, the DML benefits from its 4.6-fold lower bias and RF drive with respect to the RSOA. Moreover, the larger intrinsic e/o modulation bandwidth of the DML enables

TABLE I
COMPATIBLE PON LOSS BUDGETS FOR B2B CASE AND FEC

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			

operation without extra equalizing RF circuitry. The latter affects the power consumption of the RSOA negatively due to the excess RF drive needed to compensate the losses of the passive equalizer [5]. Despite the need for a temperature controller for the current version of the AOWC, the validated ONU needs ~400mW less power compared to the equivalent RSOA-based ONU scheme. Further improvement can be obtained with uncooled AlGalnAs SOAs for the AOWC [6].

V. CONCLUSION

An upgrade from colored to colorless ONUs using a SOI hybrid AOWC was presented. The photonic chip performs XGM-based WC with 2R regenerative properties and spectral processing with a SOA and a DI cascade, respectively. Optional chirp filtering exploitation can increase US data-rate.

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