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Symmetric 10 Gbps PON operating with a single laser over 31 dB of ODN Loss

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***Abstract* — We propose a fully-bidirectional and symmetrical 10 Gbps OOK PON solution, using the same wavelength in both upstream and downstream directions. Thanks to the remodulation performed by the ONU, it is able to transport 20 Gbps per wavelength using only one optical source for the full network, regardless the number of users. The system is based on direct-detection in downstream and self-coherent detection in upstream, over a standard 31 dB loss splitter-based PON. We experimentally demonstrate the proposed architecture over a realistic PON fiber plant with one wavelength and commercial components. We then discuss the potential application of our solution in a ITU-T G.989 NG-PON2 PtP-WDM architecture.**

***Index Terms* — Passive Optical Network, Reflective Modulation, Self-coherent detection.**

I. Introduction

The most recent and advanced standard for PON (usually called NG-PON2, and released under Recommendation ITU-T G.989, [1]) has for the first time ever introduced Dense Wavelength Division Multiplexing (DWDM) in the PON arena for both upstream and downstream. As a minimum, ITU-T NG-PON2 will use four wavelengths per direction over a 100 GHz DWDM grid, but the standard already envisions a higher number of wavelengths and a 50 GHz spacing. In particular, 16 wavelengths per direction would be required for the full implementation of the standard, using 8 wavelengths for the so-called TWDM-PON (time and wavelength division multiplexed) and other 8 wavelengths for PtP-WDM (point-to-point WDM) services. This full implementation will require tunable lasers having a wavelength accuracy at both the Optical Line Terminal (OLT) and Optical Network Unit (ONU) sides of the same level as for metro and long-haul DWDM systems. Such wavelength accuracy demand is today perceived as very critical from the component technology point of view, especially due to the consumer-electronics cost targets for the ONU.

In this paper, we propose a solution that focuses on largely reducing the complexity of wavelength handling at the customer premises, and particularly on completely removing the need of tunable lasers at the ONU. The experiment reported in this letter is based on a previous architecture described in [2, 3], largely modified to introduce bidirectional transmission over a single wavelength, so that the ONU requires only one wavelength and thus a single optical filter for both directions. This is the main novelty compared to our previous papers. This new PON network can now handle all users with only one optical source residing at the OLT and used for both downstream (DS) and upstream (US). In particular, we demonstrate a bidirectional transmission on a single-λ using On-Off Keying (OOK) at 10 Gbps in both directions, with simple direct-detection (DD) in DS, reflective modulation at ONU and self-coherent detection in US at the OLT, yielding an overall capacity of 20 Gbps. The architecture is completely compliant with splitter-based ITU-T PON Optical Distribution Network (ODN) requirements (at least 29 dB). State-of-the-art research activities on reflective PON targeting low-cost applications ([4]) have recently demonstrated over 30 Gbps per λ, but requiring complex multilevel modulations and using different wavelengths for US and DS. A potential application scenario for our work can be in the future evolutions of NG-PON2 PtP-WDM, i.e., for high-capacity point-to-point connections using dedicated wavelengths per user over a standard splitter-based PON. In fact, we obtained the same capacity as for the higher bit rate envisioned for NG-PON2 PtP-WDM (i.e. 10 Gbps per direction per λ), halving the total required number of λs. As another advantage compared to NG-PON2, our ONU is reflective and thus it only requires tunable optical filters that should be set on the same wavelength received for DS, so that straightforward power-maximization filter tuning would suffice, without any remote control from the OLT; we believe that removing the cost of tunability for what concerns the ONU transmitters justifies the cost of a coherent receiver at the OLT. It has to be pointed out that several previous papers already proposed single-λ bidirectional transmission over PON; however, they required either separated electrical bands for US and DS using single sideband techniques ([5]) and/or orthogonal modulation formats ([6]) on the two directions (thus requiring complex TX and/or RX at ONU side) or even optical frequency conversion at ONU, obtained through complex setting of ONU optoelectronics ([7]). These proposals were filter-based WDM-PON having low loss requirement for the ODN, whereas our approach allows high ODN losses, as required by splitter-based PON, or needed orthogonal modulation (as needed for example in [8]).

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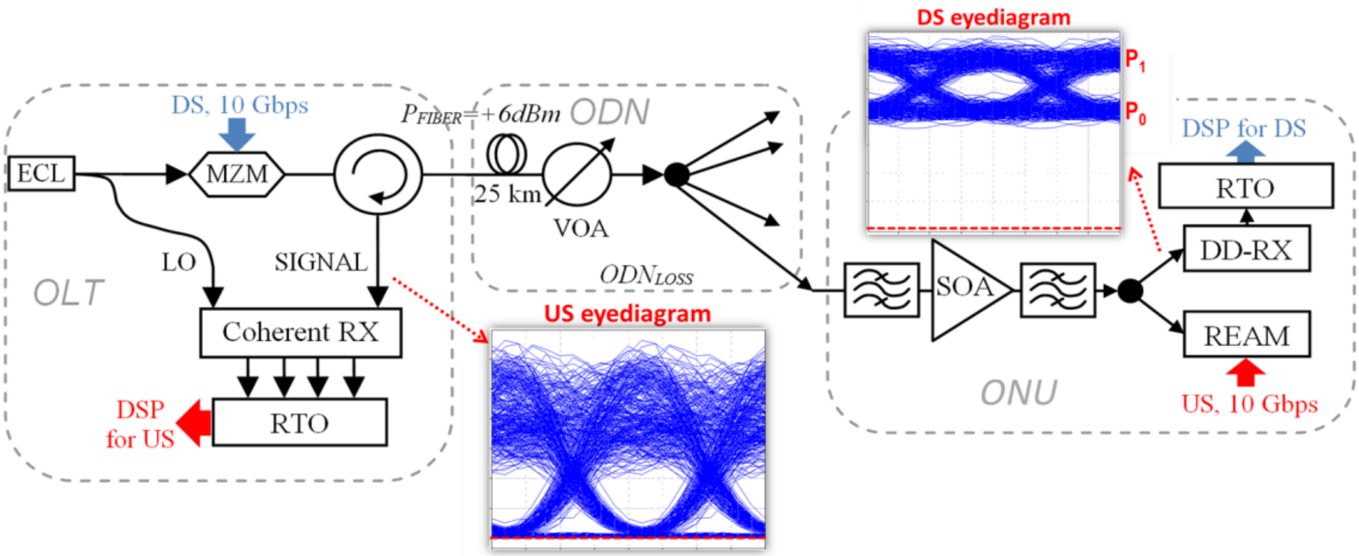

Fig. 1 Full off-line processing experimental setup (ECL: external cavity laser, MZM: Mach–Zehnder modulator, VOA: variable optical amplifier, RTO: real time oscilloscope, SOA: semiconductor optical amplifier, REAM: reflective electro absorption modulator).

Key to our architecture is taking advantage of coherent detection and digital signal processing (DSP) at the OLT to mitigate impairments on the more critical US path.

II. Experimental setup

The experimental setup is shown in Fig. 1. At the OLT, an external cavity laser (ECL, <100 kHz linewidth) is modulated with an 8B/10B OOK NRZ 10 Gbps gross data rate DS signal, by means of an external Mach-Zehnder modulator biased at the quadrature point. The resulting optical signal, after passing through a circulator, is sent to the ODN at a mean optical power set to +6 dBm. The same ECL laser is also used as a local oscillator for the OLT self-homodyne coherent detection for the US RX. The used commercial coherent receiver provides -42 dBm back-to-back sensitivity at BER=10^{-3} for 10 Gbps OOK. The ODN consists of 25 km of SMF fiber and a 1x4 optical splitter. In order to span large ODN loss ranges up to the typical ITU-T classes (about 29 dB), we added a variable optical attenuator (VOA) between the fiber and the splitter. At the ONU side, the DS signal is selected by means of an optical filter (suitable for a 100 GHz WDM grid and tuned on the λ assigned to the ONU) then amplified by a semiconductor optical amplifier (SOA) and filtered again by a similar filter to reduce ASE noise. The same filters would also act as wavelength selector in a WDM environment and avoid the SOA gain saturation when several wavelengths are transmitted in the network. For this reason, the WDM penalty with respect to the single-wavelength case (which is the working condition of this work) is negligible, as we previously demonstrated in [9]. The signal is then 1x2 split and sent to the direct-detection receiver input (for the DS signal detection) and to the reflective electro-absorption modulator (R-EAM, 6 GHz electrical bandwidth) that re-modulates it for US transmission. The DS ONU receiver is simply a direct-detection OOK receiver, which we off-line processed in order to implement some mild equalization and an accurate decision threshold optimization to improve its sensitivity and thus be able to work with low extinction ratio (ER) received signal, for reasons explained in the following. The US signal is generated by re-modulation of the DS one, driving the R-EAM with an 8B/10B NRZ signal at the same 10 Gbps *gross* data rate as the DS. The system capacity is limited by the bandwidth of our R-EAM; we are confident that, using an higher bandwidth R-EAM, we would obtain similar performance also working at a *net* data rate of 10 Gbps. We remind here that (as we explained in details in [2]) the 8B/10B code is required in our bidirectional approach to carve the low frequency electrical spectrum to limit remodulation crosstalk.

After being amplified by the same SOA (that thus acts as a bidirectional amplifier), the US signal is sent back through the ODN, then received by the OLT self-coherent receiver, whose output electrical signals are sampled by a real-time oscilloscope (RTO) and post-processed using standard DSP [10] for coherent detection, based on Viterbi-Viterbi carrier-phase estimation and Least-Mean Square adaptive equalization. We assume an US FEC threshold at BER=10^{-2} (which would require a 20% overhead, [11]) while for DS FEC we assumed a less complex code (a RS(1023,1007)+BCH(2047,1952) as in G.795.1–I.4, capable of correcting more errors than the one specified for XG-PON [12]), to correct a BER=10^{-3} with an overhead lower than 10%, since decoding needs to be implemented at the ONU side.

For sake of clarity, in the inset of Fig. 1 we plot the simulation of the US and DS eye diagrams in back-to-back conditions. In DS we are not using the modulator full range, for reasons that will be clarified later, whereas the US amplitude (particularly its high level) is affected by the DS signal, as expected since we do not implement any modulation cancelling in the remodulation process.

III. Experimental results

Working on standard splitter-based ODN, one of the most relevant figure of merit is the maximum tolerable ODN loss inducing FEC failure on the BER performance. In our proposal, it turned out that the ultimate limiting factor is the amount of tolerable crosstalk due to spurious optical back-reflection from the OLT transmitter into the OLT US receiver. In fact, using a single λ bi-directionally, optical filtering does not help in counteracting the effects of back-reflections. Signal crosstalk is primarily due to Rayleigh backscattering (RBS) along the PON trunk fiber. We showed in [3], on a similar architecture (self-coherent reflective PON but without single λ bi-directionality), that RBS generated by a DS continuous wavelength (CW) appears, after US self-coherent detection, as a low-frequency electrical noise at baseband (as shown in Fig. 2 and 3), and that can be strongly reduced by an electrical high-pass filter after coherent detection. Provided that a DC spectral carving code such as 8B/10B is used, this low pass filtering does not impair signal detection, Anyway, since in our current setup the DS signal is modulated, RBS appears as a large bandwidth interfering signal, covering the same frequency components of the useful US signal (Fig. 2).

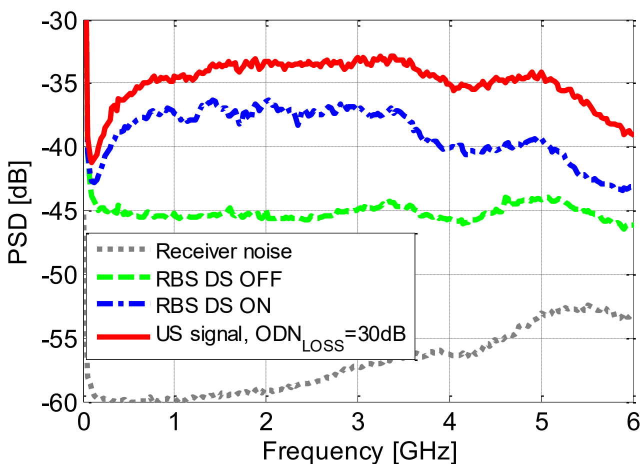

Fig. 2 RBS spectral analysis at the OLT receiver side when DS OOK modulation is switched ON and OFF.

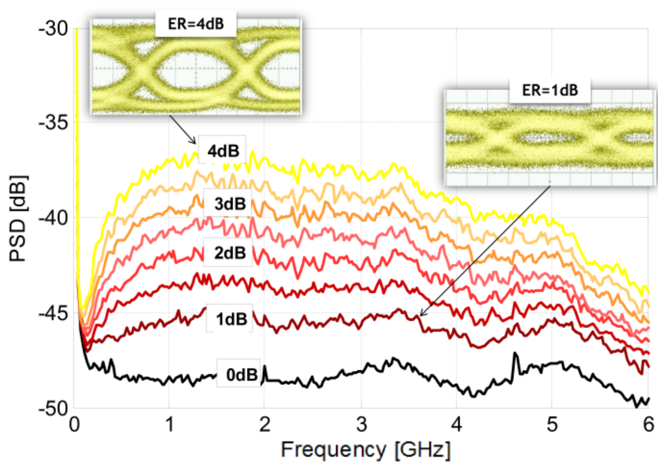

Fig. 3 RBS spectral analysis at the OLT receiver side for different DS signal extinction ratio.

For our target high ODN loss, we found that RBS average power becomes comparable with the useful US signal power at the OLT input. We thus had to reduce this "large bandwidth" RBS by decreasing the DS signal extinction ratio (ER). In fact, for a given average DS power, decreasing its ER increases the power of the CW component while reducing the modulated part of the spectrum. Decreasing the ER thus favors US performance at the expenses of DS one, as shown in Fig. 3 reporting the spurious RBS spectrum at US receiver for different DS ER. Anyway, the DS performance decreases with decreasing ER, as demonstrated by the reduction of the eye opening reported in the inset of Fig. 3. Therefore, our first system optimization step was focused on finding the optimal balance between US and DS in terms of BER as a function of the DS ER. For this purpose, we set the ODN loss to 30 dB (and SOA bias current to 140 mA), obtaining the results resumed in Fig. 4, where we plotted the US and DS BER as a function of the DS ER. As expected, a higher DS ER value corresponds to a lower DS BER and to a higher US BER.

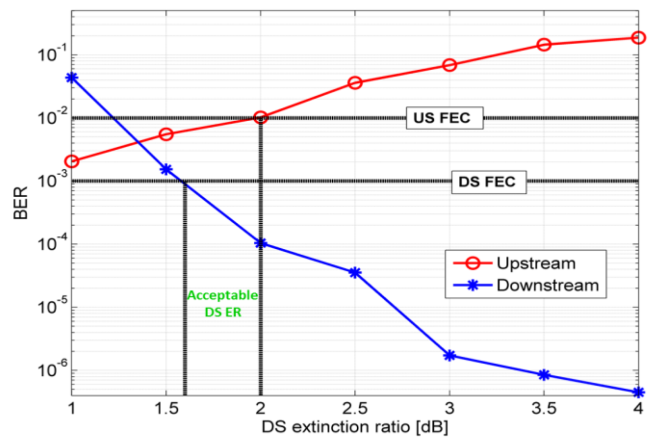

Fig. 4 US and DS signal BER vs. DS ER, ODN loss = 30 dB, SOA bias = 140 mA.

We then further optimized the system by jointly changing the DS signal ER and the ONU SOA bias current, which also turned out to be a key parameter, since its optimal value is a balance between high SOA gain and its nonlinear saturation effects. The results are summarized in Fig. 5, where we reported BER contour plots for both the US (solid red lines) and the DS (dash-dotted blue lines) as a function of the DS ER and the SOA bias (which in turns is related to the SOA optical gain). The green-patterned area corresponds to the system parameters that simultaneously provide a BER lower than the FEC thresholds defined for the US and DS transmissions (respectively 10^{-3} and 10^{-2}).

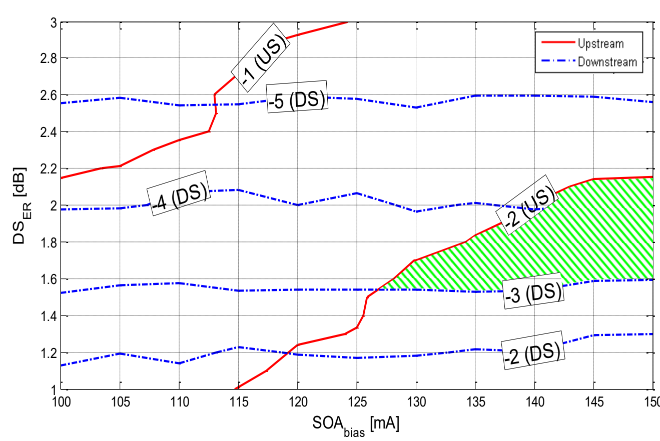

Fig. 5 US and DS contour plots of log10(BER) vs. SOA bias and DS ER, ODN loss = 30 dB.

After setting the DS ER to 1.6 dB (which turns out to be a reasonable compromise between US and DS requirements), we evaluated the BER for both US and DS as a function of the system ODN loss, after optimizing the SOA bias current for each ODN values. This parameter is mostly relevant for US performance (as shown in the contour plots in Fig. 5), so that such optimization was focused on US; the related results are reported in Fig. 6 in terms of US and DS BER vs. ODN loss. This is the main outcome of this work, demonstrating that our full-duplex transmission system supports up to 31 dB ODN loss before reaching the FEC thresholds defined for both the US and DS transmission, satisfying ITU-T ODN class N2.

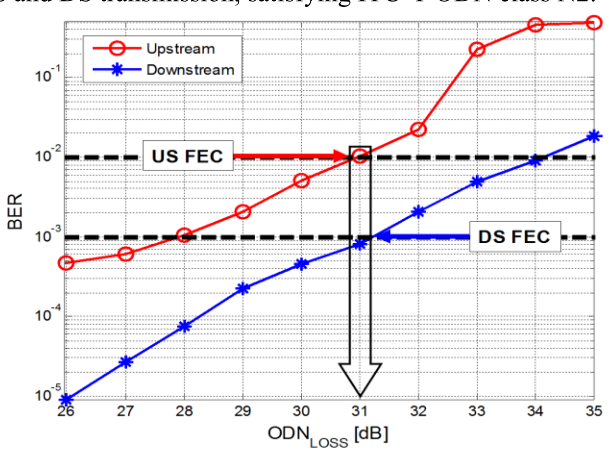

Fig. 6 US and DS BER vs. ODN loss with DS ER=1.6 dB and the optimized SOA bias current for each ODN loss.

IV. Discussion and Conclusions

The experiments shown in this paper were focused on demonstrating the bidirectionality feature, and were thus done using only a single wavelength. Anyway, the proposed architecture is specifically meant for the use in DWDM, and in particular it may allow carrying the same type of traffic required by the "Point-to-Point" NG-PON2 option (i.e. ITU-T G.989 PtP-WDM scenario), but with several distinct advantages in terms of cost/complexity, for example:

- wavelength accuracy is required at the OLT side only, since all wavelengths are generated at the OLT, whereas the proposed ONU is completely laser-less;
- if we consider a "full-fledged" implementation of G.989 PtP-WDM using 8 wavelengths per direction, it would require 16 wavelengths in total over a 50 GHz spacing and each carrying 10 Gbps, while in our proposal the required number of wavelengths would be only 8. The wavelength spacing could thus eventually be increased from 50 GHz to 100 GHz, which would surely be beneficial to relax optoelectronic component specifications;
- the ONU would thus require only tunable filters to select its dedicated λ. The control loop for the filter could be completely local to the ONU, since the filter should tune on one of the wavelengths generated at the OLT using for instance very simple power-maximization tracking at the output of the filter;
- a possible implementation of the ONU could foresee a silicon-photonics based reflective modulator, as the one demonstrated in [13] and [14], allowing for a very compact and cheap customer's premises equipment.

All these features would allow decreasing the ONU CAPEX cost, i.e., the cost of the ONU optoelectronics. Also OPEX may be reduced, thanks to the fact that wavelength control is not needed at the ONU side, thus simplifying operational complexity. The only relevant price to be paid for all these potential advantages would come from the need of a coherent receiver, which anyway in our architecture is required only at OLT side, and not at the ONU side. Even though the current cost of coherent receivers is still too high for PON applications, the situation may rapidly change, for instance due to the ongoing development of Silicon Photonic coherent-receiver platforms. In fact, several projects on coherent PON are currently ongoing worldwide, and its use is continuously reviewed in ITU-T meetings on the future evolution of PON.

References

[1] ITU-T Recommendation G.989.1 (03/13) and G.989.2 (12/14) "40-Gigabit-capable passive optical networks 2 (NG-PON2)".

[2] S. Straullu, F. Forghieri, G. Bosco, V. Ferrero, R. Gaudino, "Compatibility between coherent reflective burst mode PON and TWDM-PON physical layers," Opt. Express 22, 1, 9-14 (2014).

[3] S. Straullu, F. Forghieri, V. Ferrero, R. Gaudino, "Optimization of self-coherent reflective PON to achieve a new record 42 dB ODN power budget after 100 km at 1.25 Gbps," Opt. Express 20, 28, 29590-29598 (2012).

[4] S. Straullu, P. Savio, J. Chang, V. Ferrero, A. Nespola, R. Gaudino, S. Abrate, "Optimization of Reflective FDMA-PON Architecture to Achieve 32 Gb/s Per Upstream Wavelength Over 31 dB ODN Loss," IEEE JLT, vol.33, no.8, pp.1630-1634, April 2015.

[5] A. Lebreton, B. Charbonnier, J. Le Masson, "A Single Wavelength 25-Gb/s Symmetric FDMA PON," IEEE JLT, vol.33, no.8, pp.1630-1634, April 2015.

[6] C.W. Chow, C.H. Yeh, "Using Downstream DPSK and Upstream Wavelength-Shifted ASK for Rayleigh Backscattering Mitigation in TDM-PON to WDM-PON Migration Scheme," IEEE Photonics Journal, vol.5, no.2, April 2013.

[7] C.W. Chow, C.H. Yeh, "Mitigation of Rayleigh backscattering in 10-Gb/s downstream and 2.5-Gb/s upstream DWDM 100-km long-reach PONs," OSA Optics Express, Vol. 19, Issue 6, 2011.

[8] C.W. Chow, C.H. Yeh, C.H. Wang, F.Y. Shih, and S. Chi, "Signal Remodulation of OFDM-QAM for Long Reach Carrier Distributed Passive Optical Networks," IEEE PTL, vol.21, no.11, pp.715-717, 2009.

[9] S. Straullu, J. Chang, G. Bosco, V. Ferrero, S. Abrate, F. Forghieri and R. Gaudino, "TWDM-PON-compatible 10 Gbps Burst-mode coherent reflective ONU achieving 31 dB ODN loss using DFB lasers", 40th European Conference and Exhibition on Optical Communication (ECOC), Cannes, France, 09/2014.

[10] S. J. Savory, "Digital filters for coherent optical receivers," Opt. Express 16, 2, 804-817 (2008).

[11] N. Kamiya, S. Shioiri, "Concatenated QC-LDPC and SPC codes for 100 Gbps ultra long-haul optical transmission systems," OFC 2010, San Diego, OThL2.

[12] ITU-T Recommendation G.987.3 (01/14) "10-Gigabit-capable passive optical networks (XG-PON): Transmission convergence (TC) layer specification" – Annex B.

[13] S. Menezo, E. Temporiti, J. Lee, O. Dubray, M. Fournier, S. Bernabè, D. Baldi, B. Blampey, G. Minoia, M. Repossi, A. Myko, S. Messaoudene, L. Carroll, S. Abrate, R. Gaudino, P. O'Brien, B. Charbonnier, "Transmitter made up of a Silicon Phottonic IC and its flip-chipped CMOS IC driver targeting implementation in FDMA-PON", Journal of Lightwave Technology, Vol. 34 n. 10, pp. 2391-2391, March 2016.

[14] S. Straullu, P. Savio, G. Franco, R. Gaudino, S. Bernabè, M. Fournier, V. Muffato, S. Menezo, B. Charbonnier, E. Temporiti, L. Carroll, J. Lee, P. O'Brian, R. Marchetti, G. Duan, F. Saliou, S. Abrate, "Demonstration of a partially integrated silicon photonics ONU in a self-coherent reflective FDMA PON", To appear on IEEE JLT, 2017.