Network-embedded self-tuning cavity for WDM-PON transmitter

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Abstract: A network-embedded self-tuning cavity is proved in wavelength division multiplexed passive optical network transmission over 32 channels. The external source-less topology takes advantage of a reflective element at the remote node and a reflective semiconductor optical amplifier at the optical network unit to establish a distribution-fiber based cavity. The bit error rate performance of up to 5-km cavities is presented with two optical network units simultaneously operating and with downstream signal co presence. The experimental analysis at 1.25 Gb/s provides an evaluation of polarization dependences when exploiting low polarization dependent gain reflective semiconductor optical amplifiers with 25-km and 50-km standard single mode fiber transmission.

OCIS codes: (080.1238) Array waveguide devices; (250.5980) Semiconductor optical amplifiers; (060.4510) Optical communications.

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1. Introduction

The success of any proposal for next generation access networks (NGAN) will essentially depend on the capability to obtain scale economies, keywords are cost and simplicity. In

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particular in wavelength division multiplexed (WDM) passive optical networks (PON) [1] these keywords mainly concern the optical network unit (ONU), which should be the same for all the users. This means that ONUs should be colour-agnostic: colourless ONUs can be obtained by tunable lasers [2] of course. The injection technique performed on Fabry-Perot lasers [3] or reflective semiconductor optical amplifiers (RSOA) [4] is the subject of intensive research. Many solutions proposed in the literature exploit a seeding source placed at the optical line terminal (OLT), which propagates in the same downstream (DS) direction, but in another bandwidth with respect to upstream (US) [5], e.g. DS and upstream US wavelengths respectively in L and C bands. These solutions suffer of drawbacks arising from distributed scatterings of the seeding source in the feeder fiber between the OLT and the remote node (RN): Rayleigh Back Scattering (RS) and Brillouin Back Scattering. RS causes an incoherent crosstalk on US transmission limiting the PON ultimate bridgeable distance. A smart solution avoiding the need of external seeding sources and consequently also RS impairments is represented by the self-seeded RSOA [6], which is a promising candidate for obtaining directly modulable self-tuning ONU transmitters with reduced costs with respect to remotely seeded RSOAs. The ONU transmitter is constituted by a network embedded cavity, in fact the two mirrors are located at the ONU premises and at the RN respectively and the major part of the cavity is constituted by the distribution fiber, with the RN-AWG being the wavelength selection element. Multiple ONUs belonging to the same WDM-PON thus share the remote part of the cavity i.e. the AWG and the common mirror, which reflects back a portion of the modulated radiation, which consequently recirculates in the cavity. To bleach the recirculating modulated radiation the topology takes advantage of self-gain modulation of saturated RSOA [7].

In this contribution we evaluate the performance of multiple self-tuning ONUs, simultaneously transmitting and in presence of the related DS signals, experimentally emulating a bidirectional WDM-PON with completely passive remote node. Different distribution fiber lengths are taken into account to evaluate the impact of the evolution of the signal state of polarization on the performance of the US signal comparing performance with circulator based mirror and with Faraday Rotator Mirror (FRM)

In Section 2 the experimented WDM-PON topology is described. In Section 3 the network embedded transmitter performance is evaluated as a function of the polarization mastering, in fact the active element of the cavity is an RSOA showing polarization gain dependence, the experimental analysis will exploit a cavity topology including a common circulator-based mirror, which allows such evaluation. Long distribution fibers will be taken into account describing performance of up to 5-km cavity transmitters, birefringence impairments will be mitigated by means of a RN FRM configuration [8]. Conclusions are finally drawn to evidence acquired results.

2. Experimented WDM PON topology

Figure 1(a) shows the experimented 32-channel 1.25-Gb/s WDM PON topology. Two-twin cyclic athermal NEL AWGs with 100-GHz spacing serve as multiplexer/demultiplexer at the OLT and at the RN respectively. DS transmitter is an externally intensity-modulated tunable L-band laser, coupled to the AWG by means of C-L WDM coupler (IL=0.8 dB), which also routes the incoming US signal to the US receiver. A feeder fiber of 24 km or 50 km of SSMF links the OLT to the RN. At the passive RN, the 80/20 output coupler and the mirror are the common portion of all the ONU network-embedded cavities. In particular two different mirror topologies have been exploited, the first, including an optical circulator and polarization controllers, allows for performance evaluation as a function of polarization variations inside the cavity; the second is a Faraday Rotator Mirror with 45° rotation at 1550 nm ±1.2° over the entire C-band, to realize a configuration recently demonstrated to give almost polarization-independent operation with low PDG RSOA [8]. The remaining passive section of the self-tuning cavity is constituted by the distribution fiber, ranging from 1 km to 5 km, and by the C-L WDM coupler. Finally the gain and modulation medium is provided by two RSOAs by Alcatel-Thales III-V Lab [9], whose output gain spectra are shown in Figs. 1(b) and 1(c),

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compared with the channel allocation in C-band for the US (in black) and L-band for the DS (in red); the optical spectrum resolution is 0.5 nm. Both RSOAs are operated at room temperature by a thermo electric cooler and they have very low polarization dependent gain (PDG) in linear regime: lower than 1 dB for ONU1 and than 0.5 dB for ONU2. As can be seen RSOA2 gain spectrum does not adequately cover channels lower than 16. At each ONU the C-L WDM coupler also routes incoming DS signal to the DS receiver. All receivers include 1.25 Gb/s APD-TIA and clock and data recovery.

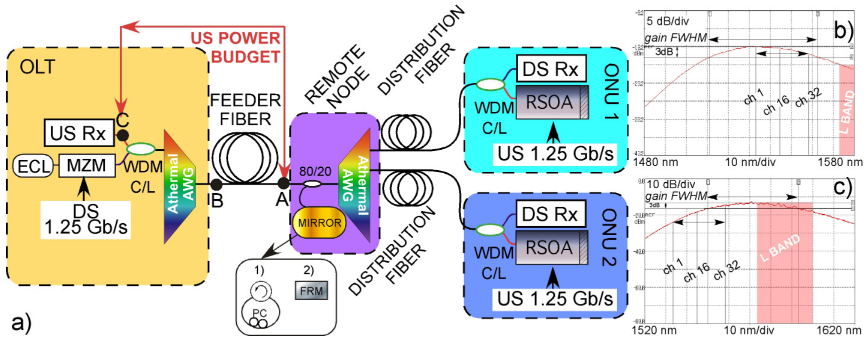

Fig. 1. (a) Experimented WDM PON topology (b) III-V Lab RSOA1 output gain spectrum (c) III-V Lab RSOA2 output gain spectrum (0.5 nm resolution).

3. Experimental results

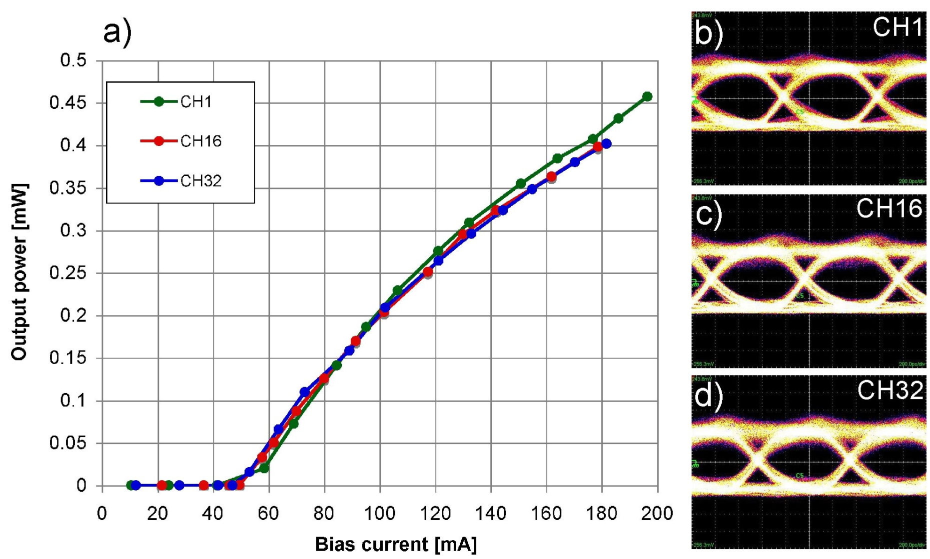

Fig. 2. (a) Optical output power vs RSOA1 bias current, for US channels 1, 16 and 32. Back to back 1.25-Gb/s eye diagrams with linear PD for (b) channel 1, (c) channel 16, (d) channel 32.

Figure 2(a) shows the power versus RSOA bias current curves for the three evaluated channels covering the C-bandwidth, for ONU1 and 1-km distribution fiber length. Optimized transmitter performance is around 160-mA bias current, corresponding to almost –4 dBm available output power. It should be reminded that output power is intended as measured at the RN, that is at point A of the Fig. 1 setup: from the ONUs point of view, point A) can be called back to back. For all the considered channels the operating point is set in the nonlinear region of the power-versus-current curve, as the RSOA has to operate in saturation condition in order to bleach the incoming recirculating-modulated radiation. Figures 2(b)-2(d) show the

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back to back eye diagrams at 1.25 Gb/s for the three channels at 160-mA bias current; CH32 shows a slightly noisier eye diagram due less effective residual modulation cancellation, being at the edge of RSOA1 3-dB bandwidth. Eyes are registered by the AC-coupled output of a linear PIN-TIA photodiode. Output ER is evaluated through the DC-coupled output of the same receiver: for all the considered channels it ranges from 6 to 6.5 dB. The output ERs are the results of the trade off between the desirable eye opening which increases performance and the capability of the RSOA to bleach the high ER of the recirculating modulation [7].

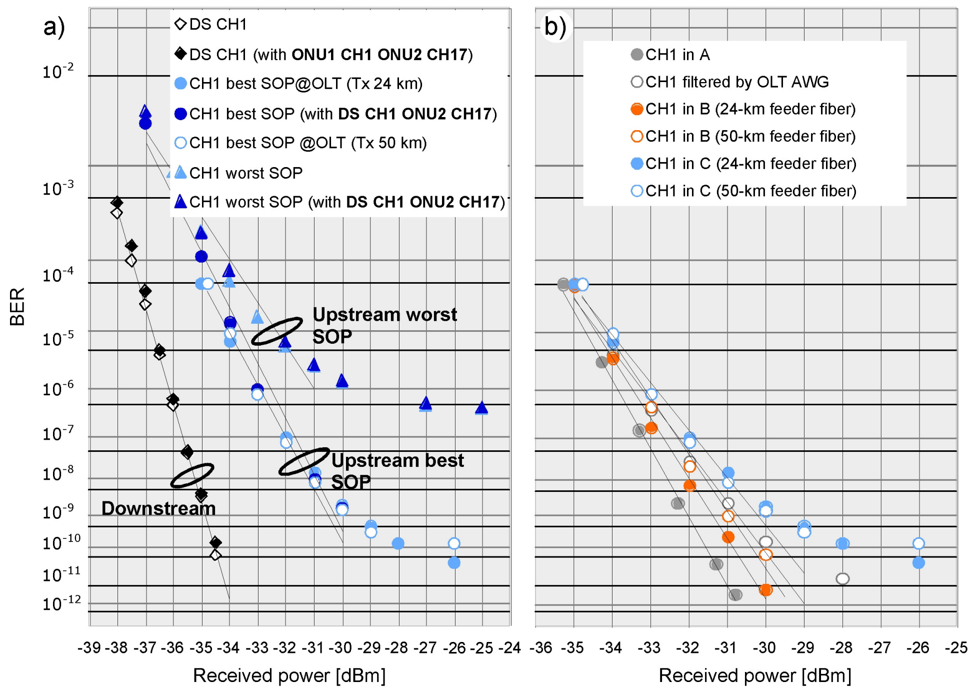

Fig. 3. BER versus received power for channel 1 at ONU1: a) US and DS evaluation with simultaneous operation of ONU2 over 24 and 50 km b) analysis of channel 1 in different measurement point of the setup for 25 and 50 km with reference to Fig. 1.

The first analysis of the embedded self-tuning cavities comprised BER measurements as a function of the received power, while simultaneously operating two ONUs respectively with 1.4 and 1 km distribution fiber, in the circulator-based mirror configuration. They have been performed for different channels in co presence of the corresponding DS signal. PRBS is 2^7-1, as this test pattern gives the closest match to the maximum run-length of a Gigabit Ethernet line code [10]. Nevertheless a back to back evaluation of pattern dependence evidences for 2^{31}-1 pattern length no penalty at 10^{-4} BER and less than 1 dB at 10^{-11} BER with respect to the 2^7-1 pattern. Figure 3 shows BER curves for ONU1 channel 1 (CH1) at 1533.4 nm, which is close to RSOA1 gain peak. For the sake of clarity curves are displayed into two different charts. Figure 3(a) assesses the lack of crosstalk impairments both on US signal and on DS signal: no penalty is in fact observed when additional channels are ON, as can be seen comparing black full diamonds curve with open diamonds curve, for the DS signal, and the dark blue full circles curve with the light blue full circles curve for US signals. By means of the fiber polarization controllers (PC) inside the optical circulator mirror (see Fig. 1) opposite SOP conditions within the cavity are analyzed: at 10^{-4} the difference between the two SOPs is around 1 dB, while at lower BER the error floor rises from 10^{-10} to $5 \cdot 10^{-7}$. Focusing on the best SOP condition, the comparison between results with 24 km and the 50 km feeder fiber, respectively light blue full circles and open circles curves, show little difference when CD load is almost doubled. In order to provide an insight on the sources of impairments in the scheme, the penalty due to OLT AWG and dispersive fiber have been measured alone.

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Results are shown in Fig. 3(b). By comparing the back to back performance of the US signal (point A in Fig. 1) (full grey circles) with that at point B after 24-km transmission (full orange circles) and 50-km transmission (open orange circles), it can be seen that the propagation penalty is slightly higher than 1 dB for the longest distance, but no error floor appears. In these conditions the modulated output spectrum bandwidth is 11 GHz and thus it is not the limiting factor for typical PON feeder fiber lengths at this bit-rate. On the other hand, the comparison with CH1 filtered by the OLT AWG without propagation (open grey circles) shows that AWG filtering evidences the 10^{-11} BER error floor, as expected due to its action on the RIN associated to the US signal [11]. The combination of chromatic dispersion and OLT AWG filtering further increases this floor.

The same measurements have been performed both for ONU1, over the C band, and for ONU2, restricting to channels from CH16 to CH32. The results in Fig. 4 have been expressed in term of available US power budget for 24-km feeder fiber, measured as the difference between the output power of the self-tuning cavity (in A) and the received power necessary to achieve 10^{-4} BER (in C) for ONU1 (Fig. 4(a)) and ONU2 (Fig. 4(b)); 10^{-4} BER was chosen as it represents 239,255 Reed-Solomon pre-FEC limit [12]. In these measurements PCs have been positioned to obtain best and worst polarization performance respectively for ONU1 (Fig. 4(a)) and ONU2 (Fig. 4(b)). It can be seen that power budget for ONU2 CH16 and CH17 is 2dB lower than for ONU2 CH32, whose wavelength is close to RSOA2 gain peak experiencing nearly the same gain as ONU1 CH1, both allowing for a power budget of 27 dB. Similarly ONU1 CH32 behaves as ONU2 CH16, which sees a similar gain, as can be seen by comparing spontaneous emission spectra of Figs. 1(b) and 1(c). The green area in the Fig. 4 represents the polarization spread, that is the difference between worst and best SOP performance. As already discussed for ONU1 CH1 even low PDG, can significantly impact on the transmitter performance as it is enhanced by multiple roundtrips during the cavity build-up [13] resulting in nearly 1 dB power budget difference at 10^{-4} and an increased error floor. The polarization spread is lower for ONU2, which relies on a lower PDG RSOA.

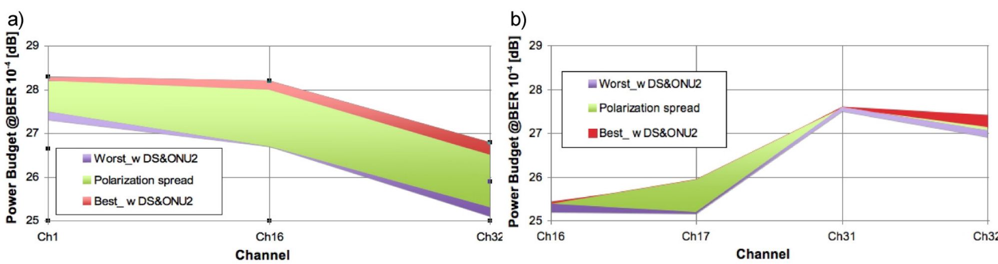

Fig. 4. Power budget at 10^{-4} BER for different channels of ONU1 (a) and ONU2 (b). The red and blue areas represent the spread in presence of the second ONU and the DS transmission respectively in best and worst SOP conditions. The green area expresses the performance differences associated to polarization variations.

It has been recently demonstrated that birefringence and polarization issues can be coped with the insertion of a FRM at the RN [8] if the RSOA PDG is not significant. In this situation the cavity shows two alternating orthogonal polarization eigenstates, thus the transmitter performance is stabilized despite polarization variations due to birefringence. This allows exploiting also longer distribution fiber for the network-embedded cavity. Due to fiber length, a 5-km cavity shows approximately 1.5-dB extra losses with respect to 1-km cavity, which are marginal with respect to experimented cavity losses due to athermal AWG, output coupler ratio, C-L WDM coupler, which average 16-17 dB. Cavity insertion losses referred to the gain balance define the performance of the self-tuning cavity.

Figure 5 presents the measurements while simultaneously operating ONU1 and ONU2 respectively with 5 and 1.4 km distribution fiber and exploiting a FRM as the common reflector. Results are quite similar to those commented in Fig. 3. No penalty is found both for the DS and US when both ONUs and DS are taken into account. The US penalty with respect

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to DS is 2.5 dB in back to back (Fig. 1 point A), comparable with that of a shorter-length cavity. Moreover at 10^{-4} 50-km transmission, at OLT receiver (Fig. 1 point C), shows almost 1-dB penalty, while a 10^{-9} floor rises. Performance of the 5-km distribution fiber cavity transmitter after 50-km transmission is almost similar to best SOP performance for 1-km distribution fiber cavity, evidencing that exploitation of a FRM at the RN well overcomes the birefringence issue when exploiting low PDG RSOA.

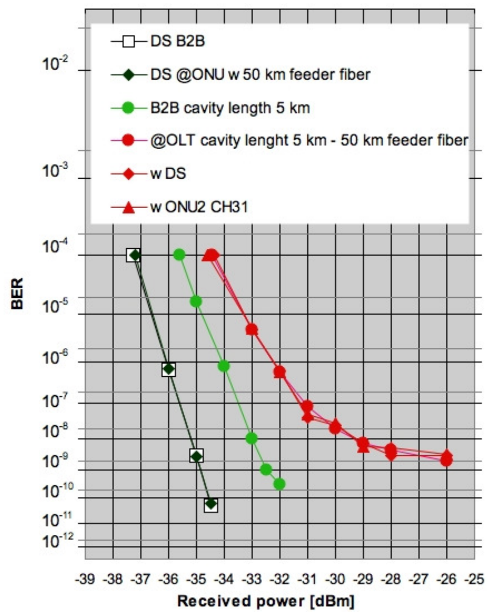

Fig. 5. BER versus received power for channel 1 ONU1 with 5-km distribution fiber length for US in: back to back (green circles) and in point C (Fig. 1) after 50-km transmission (red circles), in point C after 50-km in presence of the second operating ONU (red triangles) and in presence of the DS (red diamonds). DS performance in back to back (black open squares) and after 50-km transmission (black full diamonds) is also displayed.

4. Discussion and conclusion

We have successfully demonstrated operation at 1.25 Gb/s of a network-embedded self-tuning cavity transmitter for WDM ONUs avoiding external seeding sources. Though the remote part of the cavity is shared among all ONUs, simultaneous operation of 2 ONUs and DS signal at various wavelengths shows no cross-talk penalty. The experimental analysis has evidenced limits associated with polarization dependence due to birefringence in the very long fiber cavity; birefringence can be coped exploiting a FRM at the RN and low-PDG RSOAs, achieving 10^{-4}-BER power budget for all 32 channels (for ONU1) and over 16 channels (for ONU2) allowing transmission up to 50 km, with distribution fiber up to 5 km.

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