Time-Polarization Multiplexing for Increased Output Power of Semiconductor Optical Amplifiers in Pulsed Regime

GUSTAVO C. AMARAL1,∗, LUIS E. Y. HERRERA1, MARCELO M. RESENDE1, GUILHERME P. TEMPORÃO1, PATRYK J. URBAN2, AND JEAN PIERRE VON DER WEID1

1Center for Telecommunications Studies, Pontifical Catholic University of Rio de Janeiro, Brazil
2Ericsson Research, Ericsson AB, Stockholm, Sweden
∗Corresponding author: gustavo@opto.cetuc.puc-rio.br

Compiled June 21, 2016

We present a setup capable of overcoming the saturation output power of semiconductor optical amplifiers operating in the pulsed regime. The concept is to couple different time delays to orthogonal polarization modes, amplify the pulses multiplexed in time, and use the polarization information to recombine them into a single high-power optical pulse. Making use of a single amplifier and two polarizing beam splitters, we were able to amplify pulses with as much as 1.9 dB above the saturation output power of the device. We also show that the method is scalable if any number of polarizing beam splitters is available, where each extra device contributes with roughly 1.9 dB to the overall above-saturation amplification factor. © 2016 Optical Society of America

OCIS codes:
http://dx.doi.org/10.1364/ao.XX.XXXXXX

1. INTRODUCTION

Optical amplification is imperative for the deployment of modern long-haul point-to-multipoint passive optical networks (PONs) [1–3]. In this context, the advent of Semiconductor Optical Amplifiers operating in the 1.3 µm and 1.55 µm regions [4, 5] represented a major contribution to the fields of optoelectronics and optical networks: they exhibit high gain over a wide spectrum, low noise figure (NF), low polarization dependent loss (PDL), and fast response time. Moreover, they are usually small and need low power consumption in comparison to fiber amplifiers [6]. SOAs are particularly useful in architectures where reach extension (e.g., XGPON) is needed: in long-reach PONs, extender boxes comprised of optical amplifiers are deployed between the optical termination line (OLT) and the optical distribution network (ODN) [7].

SOAs can also be employed in centralized PON monitoring schemes for fault detection using optical time domain reflectometry (OTDR), either in the central office (CO) for tunable OTDR (T-OTDR) implementation, or in the remote node (RN), taking advantage of the presence of active elements inside the extender box [8]. Attractive due to their amplification characteristics and versatility, SOAs exhibit yet another useful feature: the possibility of acting as a high extinction ratio optical switch [9]. This behavior has been exploited in many research areas, where we take the liberty of stressing the development of high-dynamic range and ultra-high-resolution photon-counting OTDR (PC-OTDR) for single-ended in-service optical network monitoring [10–13] as one of those.

Optical fiber probing via PC-OTDR has a series of advantages over conventional OTDR, namely the elimination of dead zones, and extended measuring ranges without loss of two-point resolution [11, 14, 15]. These advantages can all be attributed to the replacement of the usual avalanche photodiode by a Geiger-mode avalanche photodiode (often dubbed the single-photon detector (SPD) module) in the reception of the backscattered signal. These devices respond to a single photon with minimum Noise Equivalent Power (NEP) and, thus, enhanced sensitivity. Unavoidably, the higher sensitivity offered by SPDs demands certain care, specially due to the contribution of Raman and Rayleigh scattering, which affect the dark count noise jeopardizing the achievable dynamic range [10, 11].

Another great concern in PC-OTDR (and in every OTDR application) is the “one-pulse at a time” condition that allows for a univocal association between the photon detection time and the scattering position. Ultimately, this condition enables one to trace the PC-OTDR profile of the fiber under test (FUT). At this point, a high-extinction ratio optical switch is imperative for PC-OTDR operation in order to guarantee the “one-pulse at a time”
A possible approach to overcoming the maximum output power of an optical amplifier would be to split the input signal into two or more spatial modes with a 1:N optical splitter and then connecting N SOAs to each spatial mode. Adjusting the relative optical delay of each branch and taking advantage of the low insertion loss of polarizing beam splitters – with a compatible polarization adjustment – is sufficient for achieving an optical signal at the output with a higher power level than that of the saturation power of each individual SOA. When dealing with optical signals in pulsed regime, however, it is possible to multiplex the optical pulses in multiple time bins instead of multiple spatial modes.

In this article, we discuss a setup for overcoming the maximum output power available for an SOA in the pulsed regime. The concept is to perform a symmetric time multiplexing and demultiplexing and placing the SOA in between these two processes: an input optical pulse is divided into two or more pulses which experiment different time delays; the multiplexing hereby presented is into two orthogonal polarization modes, but other means can be used such as wavelength; each time delay is coupled to a different orthogonal polarization mode by enforcing a difference in the relative optical path; the delayed pulses enter the SOA at different times and experiment the full amplification of the device; the amplified pulses are recombined symmetrically in time (in the same fashion they were divided, but with different time ordering) forming a high power output pulse. Ideally, the setup should overcome the maximum output power available for the SOA in 3 dB since the pulse is divided into two; should there be a higher splitting ration, the output power gain should raise accordingly.

Our experimental results show that the proposed setup can indeed offer a higher output pulse when compared to a simple SOA amplification stage. This is accomplished without the need of an extra amplifier, which consists a cost-effective solution. Synchronization of the amplification window and the input optical pulses, even though extremely important for the success of the experiment, is already a concern for regular switched SOA amplification, so no extra complexity is added to the original setup. The remainder of the article is laid out as follows. In Section 2, we present two differently devised experimental apparatus towards the same end, each of their limitations and advantages, and settle on the most promising one. The experimental results are presented and discussed in Section 3 and Section 6 concludes the article.

2. EXPERIMENTAL SETUP

The preliminary design of the experimental apparatus is comprised of: a pulsed coherent optical source; two optical polarization beam splitters (PBS); mechanical polarization controllers (PC); an SOA; two optical delay lines (OD1 and OD2); and a Digital Delay Generator (DDG). All the devices operate in the low infrared region of the spectrum, more precisely within the telecommunication C-band. The pulsed optical source, which will be used to feed the proposed pulse amplification systems, is depicted in Fig. 1: it is composed of a tunable laser source, an Erbium-Doped Fiber Amplifier, a tunable fiber Bragg grating filter, an electronic driver for the optical amplifier (represented as Pulse Gen.), and an SOA acting as an amplified high-extinction ratio optical switch. The source outputs 60 to 200 nanoseconds-wide optical pulses, the width of which may be controlled via the electronic driver; throughout the experimental validation of the proposed scheme, the width was configured as 100 nanoseconds.

The block diagram of our experimental configuration, along with the time diagrams at each point of the setup, is depicted in Fig. 2. The pulses emitted by the pulsed optical source are sent through input port number 1 of the PBS. A PC at the input of the PBS is necessary to assure that the light pulse will be equally divided between the two polarization axes of the PBS thus generating two orthogonally polarized light pulses with the same amplitude at each output arm of the device. It is useful to dub the output arms of the PBS as R (reflected) and T (transmitted): the T arm is connected directly to the SOA; the R arm is sent through one of the optical delay lines (OD1) and then through input port number 2 of the PBS, where it is again reflected thus exiting the PBS through port T, but with a time delay corresponding to OD1 and orthogonal state of polarization with respect to the originally transmitted pulse.

Note that it is imperative that the polarization in the R arm does not change until it re-enters input port number 2 of the PBS so it can be reflected once again and directed to the T arm and, thus, a PC is placed after OD1 to assure this condition. After interacting with this first PBS block, the two time-polarization multiplexed optical pulses are sent to the SOA for amplification; we shall call the first pulse (the one which went through the T arm directly) early, and the second pulse (which went through
the R arm and experimented the optical delay) late.

By adjusting the DDG’s delay relative to the sync pulse originated in the pulsed optical source, it is possible to synchronize two electrical amplification pulses to match the exact instants when the two time-polarization multiplexed optical pulses are traversing the SOA. This causes both pulses to be amplified with the full SOA gain since their temporal separation (given by OD1) is set to be higher than the SOA’s recovery time [16]. Reassembling a single high-power optical pulse in time (or demultiplexing the optical pulses) requires a second PBS to be connected at the SOA’s output with the same configuration as the first PBS: the R arm is connected to input port number 2 by a second optical delay line OD2 (refer to Fig. 2. It is imperative that OD2 exactly matches OD1 so that the pulses can be correctly reassembled. Note, also, that a PC must be connected between the SOA and the PBS’s input in order to exchange the states of polarization that enter the second PBS: the late pulse must be transmitted and the early pulse must be reflected and delayed, thus combining both in time.

The setup described above is useful to grasp the concept of the amplification method. Upon close inspection, however, we note that not only some of the adjustments in this arrangement would be rather tricky – specially when it comes to assembling two PBS blocks with the exact same optical delay – but, also, that the structure may be utterly simplified in case the SOA is able to amplify light propagating in different directions. If that was the case, a Faraday mirror at the output of the SOA would take care of exchanging the polarization states of early and late pulses, and direct the pulse back to a demultiplexing unit which is intrinsically matched with the multiplexing unit since it is the same one. An optical circulator must also be added to the new setup in order to extract the amplified pulse in a different spatial mode. The synchronization of the amplification pulses generated by the DDG, on the other hand, becomes a little trickier since, now, four light pulses will go through the SOA at different times: two on the propagating direction; and two on the counter-propagating direction. Configuring these pulses electrically in the DDG is simple enough and should not be considered a hindering factor for the new setup. The block diagram is depicted in Fig. 3 with the necessary modifications to the previous design.

3. EXPERIMENTAL RESULTS

The potential application of the proposed methodology in terms of optical amplification was assessed by four different amplifier topologies placed after the pulsed optical source: a single SOA (single pulse single pass); a circulator with an SOA placed at its port #2 with a Faraday mirror at its output (single pulse double pass); a circulator, a PBS block, an SOA, and a Faraday mirror (two time-polarization multiplexed pulses double pass); and a circulator, two PBS blocks, an SOA, and a Faraday mirror (four time-polarization multiplexed pulses double pass). The first amplifier topology (single SOA) is our reference since it represents the maximum output power of a single amplification stage. Fig. 4 depicts each of the amplifier topologies for clarity.

Fig. 4. Different amplifier topologies. a) Single SOA; b) Bi-Directional SOA; c) PBS block + Bi-Directional SOA; d) 2 PBS blocks + Bi-Directional SOA. Some of the optical devices were subtracted from the image for clarity.

In order to evaluate the system’s performance, the output of the pulsed optical source was attenuated by a variable optical attenuator and the optical output after the amplification from each of the amplifier topologies presented in Fig. 4 was measured with an Optical Spectrum Analyzer (OSA). Ideally, each extra PBS block added to the setup would introduce a 3 dB gain to the maximum output optical power since the number of pulses doubles at each stage. However, the PBSs exhibit non-zero insertion loss (0.7 dB) as well as the optical circulator (1.0 dB). Also, the pulse that goes through the R arm of the demultiplexing PBS blocks experiments its insertion loss two times., which raises the system’s intrinsic optical loss. Consequently, our expectation is that each extra PBS block would contribute with a ∼2 dB gain to the overall amplification factor. The results depicted in Fig. 5 corroborate this expectation with small deviation.

As expected, each extra PBS added to the setup increases the optical output power. A single PBS is sufficient to compensate the optical losses from the PBS’s and the circulator’s insertion loss, and two PBSs overcome the saturation output power of a single SOA. The inset of Fig. 5 is interesting as it shows that each PBS stage contributes with, roughly, 1.9 dB to the optical gain of the setup. This not only confirms our expectation but indicates that the system is scalable, and additional PBS stages may extend the saturation output power of the amplifier. In Fig. 6, we depict...
Fig. 5. Saturation curves for the four different amplifier topologies. The inset shows that each additional PBS block raises the saturation output power by 1.87 dB.

the output pulse waveform of two different amplifier topologies: the reference single SOA; and the 2 PBS blocks + bi-directional SOA, or 4 Pulses topology. The pulse waveform was measured in a 2GHz oscilloscope; an optical attenuator had to be placed at the input of the 1GHz p-i-n photodiode which detected the optical pulse in order to avoid saturating the device. We observe not only that the combined pulse maintain its original 100 ns width after amplification, but also that the 1.8 dB gain measured with the OSA is consistently observed at the scope as well.

Fig. 6. Output pulse shapes measured with an oscilloscope for a single SOA and the combined pulse using two PBSs. The pulses were measured with a conventional 1GHz bandwidth p-i-n photodiode with an optical attenuator at its input to avoid saturating the device. The gain from one configuration to the other corresponds to the one measured with the Optical Spectrum Analyzer, as it was expected.

4. AMPLIFICATION RESERVATIONS

A. Accumulated ASE Amplification Noise

Accumulated Amplified Stimulated Emission (ASE) noise is an important issue since we are dealing with a double-pass or bi-directional SOA: the ASE generated in the first pass will be amplified after it is reflected by the Faraday Mirror and traverses the SOA for the second pass. When the device reaches saturation in both passes, this is not an issue, i.e., the fraction of photons generated by spontaneous emission is negligible with respect to the stimulated emission when the number of input photons is close to the number of electrons in the conduction band that can decay to the valence band generating a photon [17]. The fact that no more electron decays can be stimulated by a traversing photon indicates that device is saturated: increasing the number of input photons will not translate into a significant increase in the amplification gain. If the device operate linearly, however, there is a significant number of electrons which are not stimulated to decay and could decay spontaneously generating ASE. From the results of Fig. 5, visualization of the ASE contribution during linear operation is not straightforward. In Fig. 7, the output versus input power is depicted in logarithmic scale.

Fig. 7. Input versus Output power curves of the four different amplification topologies in logarithmic scale (dBm). The curves are depicted inside the region of linear operation so the ASE amplification factor is more evident.

We observe that the four curves are not overlapped, but shifted. This behaviour indicates that the device is not imparting all its energy to the input coherent light signal and incoherent light is generated in the form of ASE in the first SOA pass and is then amplified in the second SOA pass. The ASE will not only inject noise to the output combined pulse, but it will also create spurious pulses that exit the amplifier topology at different times since its polarization is not perfectly combined at the PBS blocks. For that, enormous care should be taken when the device is not reaching saturation in either pass or if it designed to operate linearly.

Since the presented system was devised to operate in a high-power regime, the electronic driver which generates the current pulse for the SOA is designed to output 2 Amp pulses with a duration between 50 and 200 nanoseconds, which, in turn, causes the device to hardly operate saturated: this high-current pulse ensures a high amplification gain because the number of available electrons in the valence band is very high, but it also causes the ASE to be very high if the input pulse is low. Unfortunately, the fast electronics used in the design of the driver do not support the variation of the current amplitude so it is fixed at 2 Amps. However, if the device is designed to work outside saturation, or if the scale of PBS blocks is high enough so that the divided pulses are not enough to drive the SOA to saturation on the first pass, a different circuit can be designed so that lower current pulses are generated, hence diminishing the generated ASE. The regulation should be performed taking into account the pulse input power after the time-polarization multiplex and a 99:1 optical splitter together with a photodiode could be used for the purpose of creating a current pulse with the
right amplitude in order to satisfactorily amplifying the input optical pulses without adding an unnecessary amount of ASE to the output pulses.

**B. SOA’s Polarization Dependent Gain**

The SOA presents Polarization Dependent Gain (PDG), which can eventually hinder the pulse amplification of the time-polarization multiplex system. Even though the PDG is not too high — ~1 dB [16] —, this can be a concern, so an additional polarization controller must be added before the SOA. This way, the device’s preferred polarization axis can be set and the full amplification gain can be achieved.

Apart from the amplification gain, an extra issue arises from the SOA’s PDG: note that the amplified pulses that are combined in the first PBS block must exhibit the same amplitude so that, for instance, |H⟩ and |V⟩ produce |45°⟩ and the polarization controller between the PBS blocks can undo the transformation and align the combined pulse to the second PBS block so a single pulse is produced at the output of the amplifier topology. The additional polarization controller before the SOA, therefore, has a delicate and important role on the recombination of pulses: guaranteeing that the amplified pulses after the second pass have equal amplitudes given the SOA’s PDG.

The importance of this polarization controller can be observed in Fig. 8, where the pulse waveform at the output of the amplification unit is depicted under two different circumstances: when the polarization controller before the SOA is removed from the setup; and when the polarization controller is included and the polarization states are aligned.

![Fig. 8](image)

**Fig. 8.** Output pulse waveforms of the amplification topology with two PBS blocks when: (black) the polarization controller is removed from the setup and the polarization state recombination is unmatched; (red) the polarization states are aligned with SOA’s PDG and the polarization state recombination after the first PBS block is matched.

**5. OTDR APPLICATION**

As mentioned in the introductory part of the article, extending the dynamic range of the photon-counting OTDR setup presented in [11] and [13] would require a higher probe peak power with the same extinction rate, i.e., extending the pulse sent into the fiber without increasing the noise floor, which is crucial for a high dynamic range OTDR. From the point of view of the extinction rate, the proposed time-polarization multiplex topology and the single SOA topology offer the same value, which is the SOA’s 78 dB extinction rate [9]. Since the pulse peak power is higher when employing the 2 PBS blocks + bi-directional SOA topology, we expect that a higher dynamic range may be achieved.

In order to contextualize our amplification setup in a practical and applicable environment, the setup described in [13] (depicted in Fig. 9 for clarity) was assembled and its performance evaluated when the amplification setup represented in Fig. 9 was replaced by either the single SOA, or the 4 Pulses topology. To confirm our expectation that the amplified pulse indeed extends the reach of the photon-counting OTDR setup, the VOA at the SPAD’s input was set so that the detection rate was always constant at 10kHz. This rate was arbitrarily chosen, but represents a high detection rate which can be easily dealt with by the FPGA’s acquisition system [11].

![Fig. 9](image)

**Fig. 9.** Photon-Counting OTDR setup presented in [13]. The amplification setup right after the pulsed coherent optical source corresponds to either the single SOA or to the 4 Pulses topology.

In the case of the single SOA, the 10kHz rate corresponded to a 38.7 dB attenuation at the VOA whereas in the case of the 4 Pulse topology, this corresponded to a 40.5 dB attenuation, exactly the 1.8 dB which were expected from the measurements of Figs. 5 and 6. We depict, in Fig. 10, the OTDR traces acquired in each configuration and show that they are almost identical, i.e., the dynamic range achieved is the same even though one experiments a higher attenuation and, therefore, has a higher probing optical power.

Due to the round-trip of the optical probe pulse, in OTDR applications, each 1 dB gained in the probe power actually corresponds to 0.5 dB in terms of achievable dynamic range. In this case, the use of the 4 Pulses topology permitted a ~0.9 dB addition in dynamic range, which corresponds to a maximum achievable dynamic range of ~30 dB in the case of [13], and ~33 dB in the case of [11]. Each extra PBS block added to the amplification topology would extend this limit in ~0.9 dB.

**6. CONCLUSIONS**

Extending the amplification limit of optical amplifiers in the pulsed regime is essential for a vast number of applications in optical telecommunication. In this document, we experimentally demonstrated a method for overcoming the saturation output power of semiconductor optical amplifiers by time-polarization multiplexing and demultiplexing an input optical pulse. The system is composed of N PBS blocks which dismember the input optical pulse in 2^N pulses which are amplified, each at its own time, in a double-pass SOA with a Faraday mirror at its output. The individually amplified pulses are recombined in the same manner they were dismembered and the output optical pulse exhibits a higher power than the one achievable with a single SOA.
The amplification system was tested in a photon-counting OTDR testbed, where the achievable output optical power of a single SOA was characterized as a hindrance for achieving a higher dynamic range [11]. The system showed consistency with the measured gain over the single SOA setup in the photon-counting OTDR application. Despite its subtle dependences on the polarization alignment of the optical pulses within the optical setup, the system’s scalability and verified performance sets it as an interesting means for augmenting the output power of a pulsed optical source or amplifier.

We believe future points of investigation which may yield fruitful results are the following. Developing an electronic driver capable of varying the current pulse applied to the SOA will allow for a reduction in the accumulated ASE noise and enable the amplification system to operate either in the saturated or the linear regime. Increasing the number of PBS blocks will extend the achievable dynamic range of the photon-counting OTDR without degraded spatial resolution, which may figure as an important monitoring tool for ever longer optical links of oncoming generations of optical communications. Working with in-field amplification of data signal for long-reach PON and long-haul networks at the zero-dispersion band would also be promising since SOAs operating at 1310 nm are less expensive and no EDFAs are available.

ACKNOWLEDGEMENT

The Innovation Centre, Ericsson Telecomunicações S.A., Brazil and brazilian agencies CNPq and FAPERJ supported this work.

REFERENCES