Theoretical and experimental investigation of low-cost optical amplification for packet-switched WDM metro networks

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Optical amplification issues in packet-switched networks are often underestimated. In fact, EDFAs have been shown to be seriously impaired by burst-mode packet traffic, due to their internal time-dependent gain dynamics. In this scenario, Linear Optical Amplifiers (LOA) may find an interesting and cost-effective application. LOAs are novel gain-stabilized low-cost SOAs, which already received much attention for cross-gain modulation (XGM) suppression in WDM transmission. In this paper, we present a detailed experimental and theoretical investigation on LOAs used as key amplification blocks for burst-mode packet applications and, in particular, in the MAN WDM packet network demonstrator "WONDER".

1. Introduction

Packet-switched optical networks are today widely studied by several R&D groups worldwide. While it is recognized that the introduction of packet switching directly at the optical layer would give clear advantages in terms of network simplification, the technical feasibility is still to be clearly demonstrated. In fact, the transition from continuous circuit-switching wavelength division multiplexing (WDM) optical transmission to WDM burst-mode packet switching poses very hard challenges in terms of optical components functions and performance. Among others, one of the issues to be carefully addressed is optical amplification. Amplification in packet-switched optical networks calls for specifications that are quite different from those of standard WDM transport networks. In particular:

• Amplifiers need to handle bursty input traffic with negligible penalty, i.e., a time-varying input optical power with time constants of the order of the packet duration;

• Due to the large number of (passive) optical components used for optical signal processing (such as WDM mux/demuxes, switches, couplers/splitters), most of the recently proposed packet architectures require several amplifiers per node, each usually with relatively low gain. Consequently, amplifiers should be compact, power-supply efficient and, ultimately, low cost. Considering these requirements, the use of standard EDFAs is clearly out of the question. Besides high footprint and cost, EDFAs show severe impairments when fed with bursty optical signals [1].

Even when gain-clamped [1], they are usually too expensive and bulky for packet switching application. Semiconductor optical amplifiers (SOAs) are a good candidate in terms of footprint and cost (provided that they can reach mass production), but have severe limitations due to cross-gain modulation (XGM). Their gain-clamped version [2] mostly solves the problem of XGM but, due to relaxation oscillations, may introduce an eye opening penalty at high bit rates close to the stabilizing laser relaxation oscillation frequency (≥10 Gbit/s). Recently, modified SOAs, called Linear Optical Amplifiers (LOA), have been introduced, in which gain clamping is achieved by integrating vertical-cavity stabilizing lasers on the direction perpendicular to the main cavity [3]. These devices have been shown to achieve good linearity (i.e., essentially constant gain and low XGM) even under varying input WDM traffic, thus acting as "gain block" elements.

In this paper, we present a detailed experimental and theoretical characterization of LOAs under packet-switched input traffic, demonstrating that they are good candidates for next-generation packet-switched optical networks, such as the "WONDER" experimental network testbed under development at Turin Politechnic.

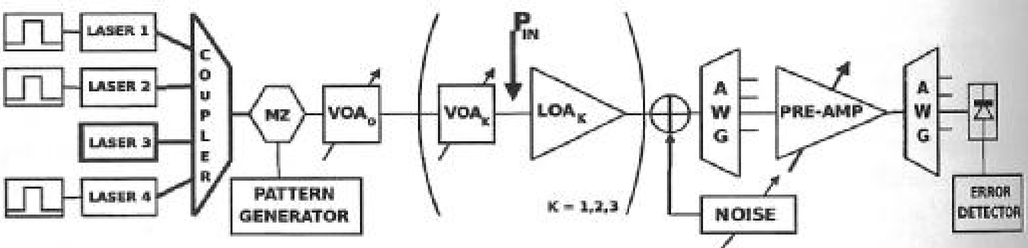

Figure 1: The experimental setup for evaluating BER vs. OSNR curves, for various LOA input powers P_{IN}.

2. Experimental results

A four-channel WDM transmission experiment was set up as shown in Fig. 1, each channel being intensity modulated and directly detected at the receiver (IM-DD). The four wavelengths, taken from the ITU grid, are λ_1=1548.51nm, λ_2=1549.32nm, λ_3=1550.12nm and λ_4=1550.92nm. The setup emulates transmission over three identical spans, each composed of a transmission fibre followed by an LOA for power recovery. Since in a metropolitan environment the spans are supposed to be short (a few kilometers), chromatic dispersion effects can be neglected. Moreover, moderate power levels are employed for transmission, so that nonlinear distortions related to Kerr effects in the fibre are usually negligible. Hence, the transmission fibre and all the optical components present in a node were emulated by a variable optical attenuator (VOA).

In order to emulate packet transmission, each laser was modulated at two levels: the presence/absence of a packet was realized via an external signal generator which directly modulated the laser injection current, while the presence of bits was realized via an external Mach-Zehnder modulator. We used three independent packet generators, for channels λ_1, λ_2 and λ_4, while λ_3 was the test channel, with a continuous modulating bit stream. The packet duration was 1 microsecond, and packet arrivals followed a Poisson point process. Since the lasers were directly modulated by the packet generators, a very large on/off power ratio (more than 35 dB) was achieved, so that the channels were effectively switched off in the absence of a packet. The packet generators were driven by the main parameter in our experiment, namely, the *traffic load* L, i.e., the fraction of time during which a channel is active. A traffic load of L=0.1 means, for instance, that each of the three interfering channels (λ_1, λ_2 and λ_4) was active for 10% of the time.

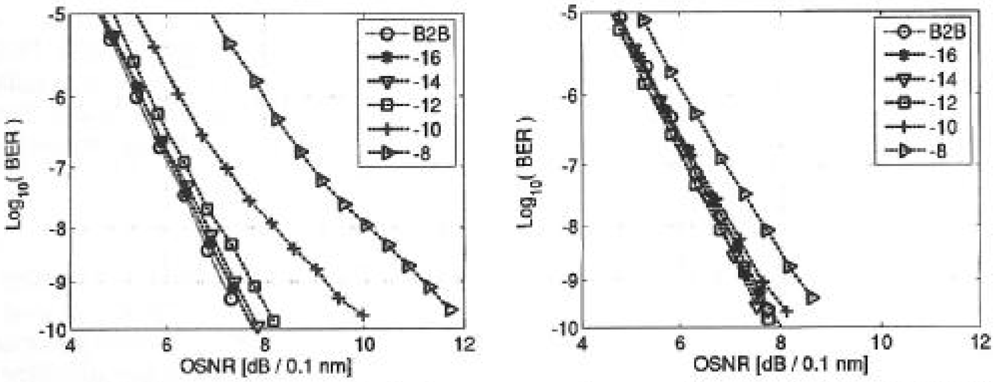

Figure 2: BER vs. OSNR curves for the two extreme values considered for traffic load: left, L=0.1; right, L=0.9. In both figures, the legend reports the P_{IN} values in dBm.

The four channels are coupled in a WDM multiplex and reach the external Mach-Zehnder modulator through polarization maintaining fibres (PMF), where they are *synchronously* bit-modulated. The modulator is driven by the pseudo-random bit sequence (PRBS) generator (with periodicity 2^{31}-1) of the BER tester (BERT), with a bit-rate R=1.25Gb/s and an extinction ratio r=12dB. The bit-synchronous operation represents a worst case with respect to the realistic case where the channels are independently modulated, since when a mark is present on the test channel it is also present on every active channel, hence pushing the amplifier *closer to saturation*.

VOA_0 in Fig. 1 was adjusted so as to obtain a certain *average* input power P_{IN} to the amplifiers. This figure determines the amount of saturation of the LOAs, and was the second parameter of interest in our experiment. Of course, since P_{IN} is an average power, the average power per active channel P^{ch} depends on the traffic load L through the relation $P^{ch}=P_{IN}/(1+3L)$, where all the channels have the same power when active. The attenuation of the k-th VOA was matched to the gain of the k-th LOA, so that the average input power to each span corresponded to the average output power $P_{OUT}=G{\cdot}P_{IN}$, being G (≅16dB) the nominal gain of the LOA, as reported in Fig. 6 (right).

At the receiver side, ASE noise was added to the multiplex and its power spectral density was varied in order to measure the BER at different optical signal-to-noise ratios (OSNR), as measured on a 0.1nm bandwidth right after noise loading. Note that any loaded noise level used in the experiments was large enough to assume that ASE noise due to the LOAs is negligible. The test channel was then selected through an AWG demultiplexer, acting as an optical filter with bandwidth B_0=0.75nm. The receiver photodiode, with two-sided electrical bandwidth matched to the bit-rate, was preceded by a last gain element (preamplifier), with negligible noise, in order to keep the average received power of the test channel at P^{test}=-8dBm.

Measurements were performed by varying the traffic load L from 0.1 to 0.9 in steps of 0.2, hence scanning different levels of network activity. For every traffic load, a set of BER vs. OSNR curves was measured, each characterized by a given average input power P_{IN} causing different amounts of amplifier saturation. P_{IN} was varied from -16dBm to -8dBm, in 2dB steps. The BERT decision threshold was manually adjusted, in order to minimize the OSNR for a single BER value. As an example, we report in Fig. 2 the BER vs. OSNR for the case L=10% (left) and L=90% (right), for the specified levels of P_{IN}. A sixth back-to-back curve is added for reference. As seen in the figure, larger values of P_{IN} push the LOAs closer to saturation, hence causing performance degradation due to nonlinear crosstalk.

3. Simulation results

A distinctive feature of LOAs is the gain clamping implemented by a vertical laser field, which induces very fast gain dynamics, i.e., the ability to recover from saturation almost instantaneously (in a few picoseconds). As a consequence, we can consider "saturation events", i.e., all channels are ON and the amplifier input power exceeds the linearity range, to be instantaneous. This is opposed to the case of erbium-doped amplifiers (EDFA), where the recovery times are long (in the order of milliseconds), hence causing packet induced crosstalk for a whole sequence of subsequent bits in the test channel. In addition, the intra-bit relaxation oscillations, seen in gain-clamped semiconductor optical amplifiers (GC-SOA), are much smaller with LOAs, especially at high bit-rates [4]. Hence, cross-gain modulation can be modelled as a memoryless effect and regarded as an instantaneous gain reduction on those mark bits on the test channel that are accompanied by one or more active packets on the interfering channels. The fast recovery times make the crosstalk on the various bits independent of one-another, hence the only parameter that counts for quantifying the penalty is the traffic load, while the network is insensitive, in this respect, both to packet duration and to the traffic statistics (here Poissonian). Note, on the contrary, that in a network using EDFAs, the traffic statistics can be a critical issue [1]. Following these observations, we can resort to a "static" model for the LOA, which accounts only for the gain vs. input power characteristic, shown in Fig. 6 (right), and adopt an approach similar to that of [5].

Going more in details, once the traffic load L is selected, in an N-channel WDM system (N=4, in our case), we concentrate our attention on the test channel. The probability of having k active interfering channels, i.e., channels sending packets that cause crosstalk on the test channel, is given by the binomial distribution $a_k = \binom{N-1}{k} L^k (1-L)^{N-1-k}$ (k=0,1,...,N-1). Given that marks and zeros have the same a-priori probability, and since all channels are bit-synchronously modulated, we will have a power $(k+1)P_b$ at the amplifier input with probability ½ a_k, where b=0,1 is the transmitted bit. In turn, for an input mean power P_{IN}, and extinction ratio r, we have $P_1 = \frac{2}{1+r}\frac{P_{IN}}{1+3L}$ and $P_0 = \frac{2r}{1+r}\frac{P_{IN}}{1+3L}$. Hence, with N=4, there are 8 possible instantaneous input power levels for the amplifiers, which in principle correspond to 8 different gain values, from Fig. 6 (right). We calculate the histograms of the power levels and of the gain values and, from these, iterate the procedure along the link so as to get the distribution of the power levels input to the preamplified receiver. BER evaluation follows a standard approach under the

Gaussian approximation, with all sources of noise taken into account (thermal noise, shot noise, signal-ASE beat noise and ASE-ASE beat noise) with their respective contribution to the total noise variance [5]. This very simple procedure requires no signal propagation, yields extremely fast calculations and relies on the fast gain dynamics of the amplifier, which permits a "bit-by-bit" evaluation of BER.

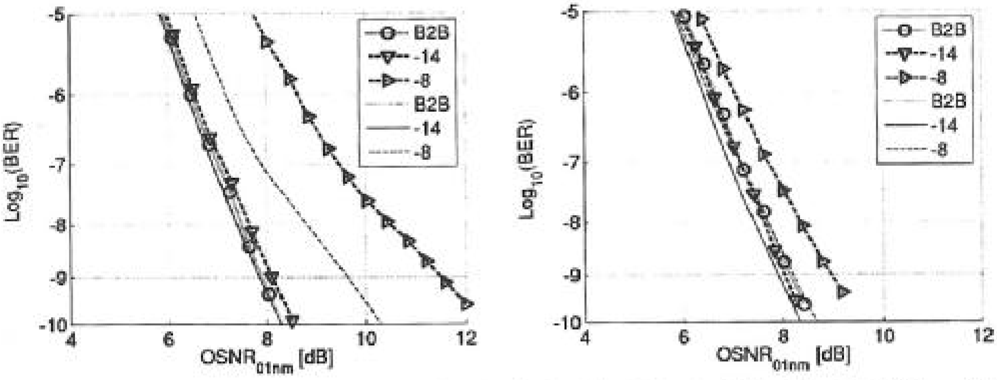

Figure 3: BER vs. OSNR curves obtained by simulation (lines), for traffic load L=0.1 (left) and L=0.9 (right). The legend reports P_{IN} values in dBm. Experimental results are reported, for comparison, with symbols, as in Fig.2. For clarity, only P_{IN} values of -14dBm and -8dBm have been reported.

In Fig. 3 we report the simulation results, for the same traffic loads considered in Fig. 2, along with the experimental BER curves for comparison. Although simulations underestimate the BER, they capture the progressive degradation due to cross-channel effects. In fact, a penalty is introduced by increasing the amplifier mean input power P_{IN} and such a penalty is much more relevant when the traffic load is lower.

Both in measurements and in simulations, the decision threshold is adjusted, once for each BER curve, so as to optimize the sensitivity for a given BER (around 10^{-7}). Hence, it is expected that the BER curves change their slope around this point, where the bit errors become unequally distributed on marks and zeros due to a suboptimal threshold (see Fig. 3). In fact, the receiver decision threshold is a key issue in a packet switched network environment. In order to further investigate its role, we report in Fig. 4 the performance obtained by simulation in the case L=0.1, by using two radically different criteria for setting the threshold, the first being extremely practical and the second rather ideal. In the left figure, results are obtained by setting the threshold to the average detected value. In terms of received optical power, this corresponds to the sum of all possible $(k+1)P_b$ power levels, weighted by the probabilities of occurrence ½ a_k. From a physical standpoint, such a criterion can be realized by using and AC-coupled photodiode, which eliminates the DC component, and by setting the decision threshold to zero. In Fig. 4 (right), the decision threshold is calculated adaptively for each OSNR value and for each possible number (k=0,1,...,N-1) of interfering channels, by using the minimax criterion with a-priori knowledge of signal levels and noise levels. From a physical standpoint, this corresponds to the ideal situation in which the receiver senses the network load (how many channels are active) in every bit period and instantly adapts the threshold accordingly. This ideal situation can be partially achieved for a system equipped with a burst-mode receiver with packet-by-packet *adaptive* threshold. As can be seen, totally different performances are obtained.

In the first case the penalty due to XGM is dramatically large, even in the back to back configuration, while in the second case it is very small and all curves almost coincide with the back to back curve, except when P_{IN}=-8dBm.

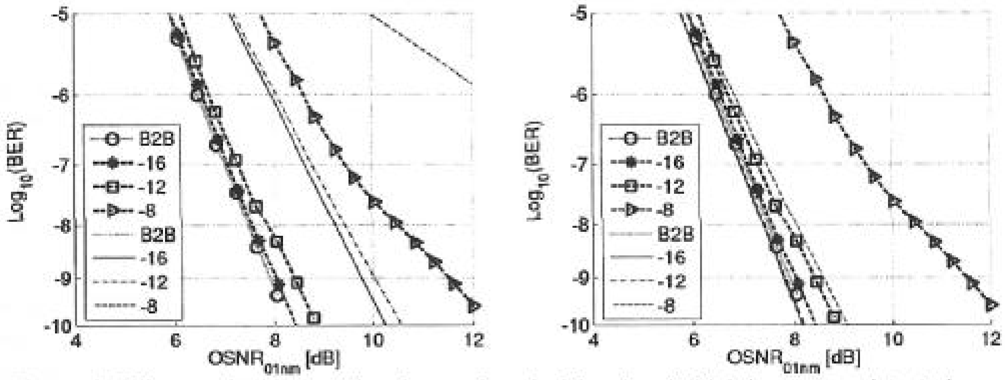

Figure 4: Different criteria for setting the receiver decision threshold: left, average detected current; right: optimal adaptive minimax threshold. The legend reports P_{IN} values in dBm. Experimental results are reported, for comparison, with symbols. Considered P_{IN} values: -16dBm, -12dBm, -8dBm.

4. Discussion and conclusions

Our aim is to isolate the penalty due to the saturation of the LOAs, related to XGM. From each set of BER vs. OSNR curves, obtained either by measurements or by simulations, a Sensitivity Penalty curve is derived, as shown in Fig. 5. Penalty is evaluated at a BER=10^{-9} and is plotted versus the average input power P_{IN}, which determines the average operating point of the amplifiers, and is thus the dominant source of gain saturation. Five penalty curves are collected, both for experimental data and for simulations, each labelled by the corresponding traffic load.

As noted in the previous section, the simple theoretical model used for the simulations underestimates the penalty. This can be due to other nonlinear crosstalk effects neglected in the model, such as four-wave mixing (FWM) generated *inside* the LOA. Although the power levels used for transmission are moderate, justifying the neglect of Kerr effects in the transmission line, it is known that in a saturated Semiconductor Optical Amplifier (SOA) such effects are enhanced, its nonlinear refractive index being orders of magnitude larger than in transmission fibres [6].

As is clearly visible in Fig. 5, the penalty is negligible until the average input power increases beyond a certain threshold, which in turn depends on the traffic load. Such threshold can be roughly located between -12 dBm and -10 dBm. In the interpretation of these results, the increase of the penalty with P_{IN} is no surprise, since the right part of the figure corresponds to having the amplifiers more saturated. On the contrary, it is counter-intuitive that the larger penalties (and the larger increase rate with P_{IN}) are associated with smaller traffic loads. In fact, one could reasonably think that, when the network is less active, i.e., L is smaller, less channels interfere with the test channel, in the average, hence producing less crosstalk. The explanation of this apparent contradiction is related to the fast recovery times of the LOAs. As previously noted, a "saturation event" has to be regarded as istantaneous and independent of the neighbouring bits. Hence, when all four channels are active, i.e., a packet is being sent by all transmitters, and a mark is being transmitted in a specific bit-period, then, since our setup is bit-synchronous, the amplifier input power reaches a maximum and the gain compression effect is maximum as well, giving rise to a reduced gain for that specific bit on the test channel. Hence, a lower power level is detected at the receiver, and thus a worse BER. Note again that such an event will not affect the following bit, for which the amplifier gain will be immediately recovered. In order to quantify the maximum gain compression, a simple calculation yields the maximum amplifier input power. If P_{IN} is the average input power and L is the traffic load, then, as already noted, the average power per active channel (and in particular for the test channel, which is always active) is $P^{test}=P_{IN}/(1+3L)$; clearly, when a logical "1" is transmitted, the peak instantaneous power $P_{peak}^{test}=2P^{test}$ is attained on the test channel, and the synchronous presence of three other marks on the interfering channels brings the total amplifier input peak power to $4P_{peak}^{test}$. It is this figure that determines gain compression and it is inversely proportional to L. As an additional confirmation of this hypothesis, we can check this figure against the amplifier gain curve, reported in Fig. 6 (right). If we assume that gain saturation starts at input powers around P_{sat}=-4dBm, we can calculate what value of P_{IN} is necessary to attain saturation with the peak instantaneous power $4P_{peak}^{test}=P_{sat}$, for the considered values of traffic load. The result is a value varying between -12dBm and -7dBm, i.e., the P_{IN} interval for which the penalty becomes appreciable in Fig. 5, with the lower values corresponding to the lower traffic loads.

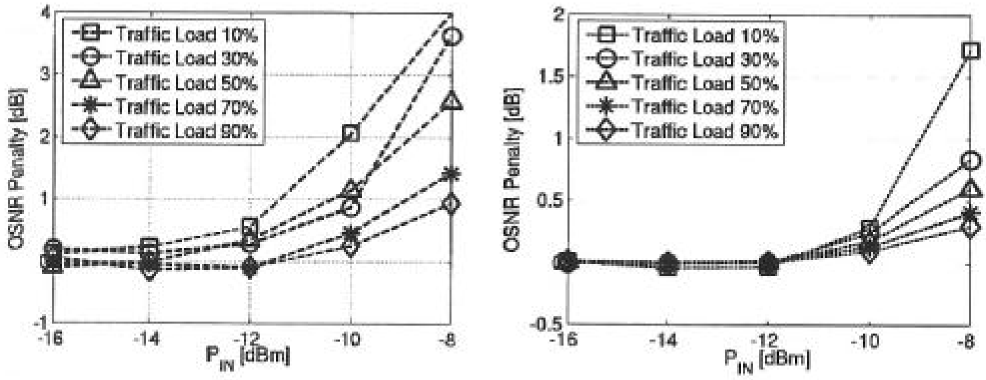

Figure 5: OSNR penalty curves (@BER=10^{-9}) for different amounts of network traffic load L. (left) experimental results (see Fig. 2); (right) results obtained by simulation (see Fig. 3).

To summarize, we can state that when using amplifiers with fast gain dynamics, such as LOAs, the average input power is not a good metric to quantify the impairments due to XGM. Rather, the network design guidelines should account for the instantaneous peak amplifier input power, i.e., to the worst case situation, which determines the penalty. The results reported in Fig. 6(left) support this statement. The five curves, each associated to a traffic load L, are nothing but those already seen in Fig. 5 (left), redrawn versus the peak power of the test channel P_{peak}^{test}. As we can clearly see from the figure, the variations in the LOA input traffic have negligible impact on the penalty and, for all values of L, a penalty of 1dB is reached for an input peak power per channel ranging from -11dBm to -10dBm. Hence, considering the nominal gain G (≅16dB), we can safely assume error-free transmission when the output peak power per channel is below 5 dBm, regardless of the network load.

Of course, given the same P_{peak}^{test}, slightly better performance is obtained for L=0.1, in Fig. 6(left), since the worst case situation (a logical "1" on both the test and the three interfering channels, producing a LOA input peak power equal to $4P_{peak}^{test} = P_{sat}$) is less likely to occur for this traffic load. In addition, as previously pointed out, the fast gain dynamics of the LOA make the network insensitive to the traffic statistics, here assumed Poissonian.

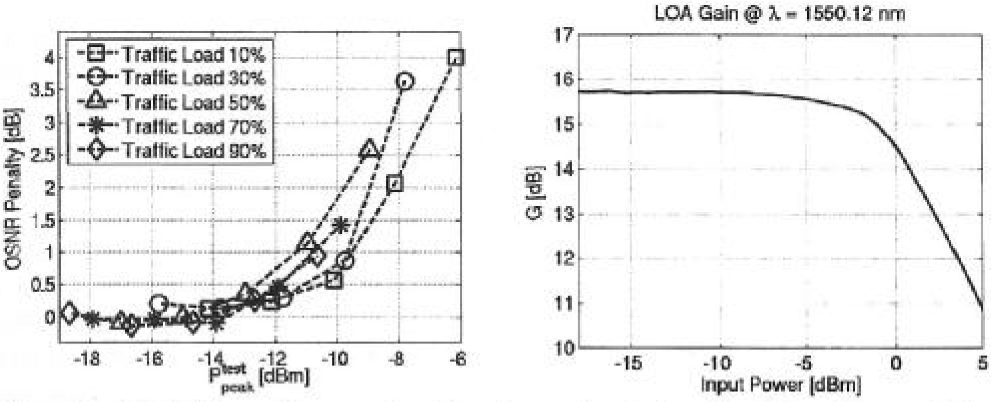

Figure 6: (left) OSNR penalty curves for different amounts of network traffic load L: same data as in Fig.5(left), recast versus the input peak power of the test channel. (right) Experimental Gain curve, measured vs. input power.

Finally, the impact of XGM on performance can be basically attributed to the necessity of setting one specific decision threshold at the receiver: power fluctuations caused by interferers make this threshold less effective due to gain saturation. There would be no penalty if the threshold were able to track and follow the number of interferers instantaneously.

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