The Impact of Polarization-Dependent Gain on the Design of Cascaded Semiconductor Optical Amplifier CWDM Systems

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***Abstract*—We derive an engineering methodology and study the impact of polarization-dependent gain (PDG) on the design of cascaded semiconductor optical amplifier (SOA)-based coarse wavelength-division-multiplexing systems. System specifications can be determined based on receiver optical signal-to-noise ratio (OSNR) requirements and cascaded-SOA OSNR penalty calculations that include a simplified model to calculate PDG statistics.**

***Index Terms*—Amplifiers, networks, optical communications, polarization-dependent gain (PDG).**

I. Introduction

SEMICONDUCTOR optical amplifiers (SOAs) have been proposed as cost-effective multichannel coarse wavelength-division-multiplexing (CWDM) amplifiers for possible CWDM system reach extension into metro regions [1]. Recent improvements in broadband SOAs [2], as well as demonstrations of cascaded SOA-based hybrid amplifiers [3], suggest that polarization-dependent gain (PDG) and noise figure (rather than gain flatness and saturation-induced crosstalk) are becoming the predominant performance factors. Although the maximum PDG for the best commercial SOAs can be specified as low as 0.5 dB over the C-band ($\sim$30-nm bandwidth), CWDM-capable SOAs typically exhibit PDGs of 1 dB or more over their 70-nm band (four CWDM channels). As cascaded SOA-based CWDM systems gain commercial acceptance, and push towards extended reach in metro regions, having a design methodology that deals with PDG is very valuable.

This letter presents the above-mentioned engineering methodology. A simulation model, that has been benchmarked with multichannel experimental system data [3] and a receiver characterization experiment [4], generates the PDG-induced statistical optical signal-to-noise ratio (OSNR) performance of the system. The impact of PDG through a cascade of SOAs is calculated based on a simple approach that reduces the computational complexity associated with Monte Carlo techniques. The system engineer can then use the derived data to design the system and/or determine PDG specifications for the SOAs taking into account system margin, other competing transport layer effects, and doing variability studies on parameters such as gain flatness and noise figure.

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II. System Simulation Model

The simulation models CWDM propagation through cascades of suppressed water peak fiber spans (80-km spans) and SOAs. This is intended to simulate a typical metro system or network path as discussed in [4]. To model each SOA and to include the PDG effect, the simulation uses a polarization beam splitter and a combiner and two simple amplifier models, one for each maximum/minimum gain polarization axis [4, Fig.1(b)]. We focus on a channel at 1550 nm and assume a typical maximum amplifier gain of 17.5 dB (i.e., gain for the maximum gain polarization axis amplifier) and a PDG of 1 dB (i.e., 16.5-dB gain for the minimum gain polarization axis amplifier). Each simple amplifier has a noise figure of 6.5 dB but the entire SOA model results in a noise figure of 6 (maximum gain polarization) and 7 dB (minimum gain polarization) Finally, span loss is made equal to maximum gain (17.5 dB). These parameters represent relatively moderate to high performance devices. Although simple, the above SOA model sufficiently captures the rotation of the amplified spontaneous emission (ASE) polarization vector and has been verified with the experiment described in [3]. External modulation is chosen to avoid any potential dispersion/chirp effects that will mask issues related to PDG. Channel launched power for maximum gain polarization is -1.77 dBm, well below the reported SOA saturation powers in [3] so gain-saturation-induced crosstalk and fiber nonlinear effects can be safely neglected. Parameter values can vary to accommodate different system needs. The modeled receiver is based on the measured performance of a CWDM demultiplexer followed by a commercial OC-48 avalanche photodiode (APD) receiver at 2.5 Gb/s and $2^{31}-1$ pseudorandom bit sequence. In our Virtual Photonics Inc. simulation model, the APD receiver uses a deterministic sampling and thresholding module with a Bessel electrical filter (2.1-GHz 3-dB bandwidth). The measured power penalty at 10^{-9} bit-error rate as a function of OSNR is represented by solid diamonds in Fig. 1 and is in good agreement with the simulation data (open diamonds). The OSNR measured in 0.1-nm resolution bandwidth is defined as signal power at a

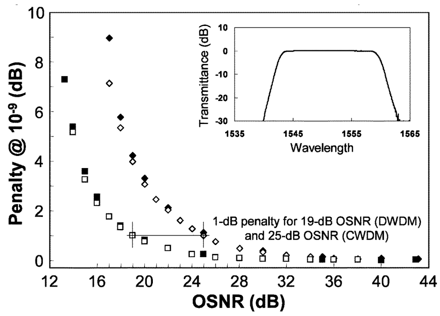

Fig. 1. APD receiver characterization for a CWDM channel (solid diamonds) and a DWDM channel (solid squares) at 2.5 Gb/s. The CWDM configuration uses a CWDM demultiplexer with 17-nm 3-dB bandwidth (inset). The DWDM configuration uses an optical filter with 0.25-nm 3-dB bandwidth. Simulation results (open symbols) closely match the experiment.

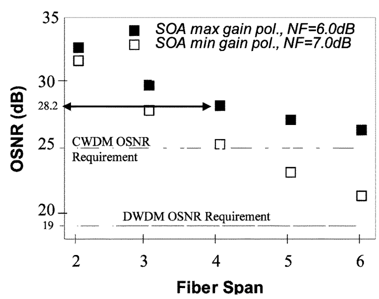

Fig. 2. Simulation results for OSNR after transmission versus fiber span in the case of SOA PDG of 1 dB and noise figure of 6.0 (maximum gain polarization) and 7.0 dB (minimum gain polarization). Polarization aligned to the maximum (minimum) amplifier gain axis is shown by solid (open) symbols. In general, for n fiber spans, there are $n - l$ SOAs in the cascade. Channel input power to each SOA stage for maximum gain polarization is -19.3 dBm.

given polarization divided by total noise over minimum and maximum gain polarizations.

As a baseline, we also plot experimental and simulation performance of the receiver using a narrow 0.25-nm optical filter typical of dense WDM (DWDM) systems (squares). The data in Fig. 1 shows a significant increase in power penalty for the CWDM configuration due to the ASE–ASE noise contribution at the receiver associated with the much wider 17-nm 3-dB passband of the CWDM demultiplexer (inset to Fig. 1). Specifying a worst-case power penalty of 1 dB requires an OSNR of at least 25 dB for CWDM as compared to 19 dB for a DWDM system. While the absolute values of required OSNR depend on our choice of commercial receiver and the fact that our model assumes no forward-error correction, the relative performance difference between the CWDM and DWDM receiver depend fundamentally on the difference in optical channel bandwidths.

Fig. 2 plots the OSNR performance after transmission through cascaded SOAs based on the described model. The range of performance is determined by separate simulations for the best-case scenario of polarization aligned to the maximum amplifier gain axis and the worst-case of polarization aligned to the minimum amplifier gain axis. The two horizontal dashed lines in the figure represent the minimum required OSNR for DWDM (19 dB) and CWDM (25 dB) receiver configurations. It is clear from the figure that based on the SOA parameters (PDG $= 1$ dB and noise figure: 6.0-dB maximum gain polarization and 7.0-dB minimum gain polarization) and assuming worst-case polarization alignment, 320-km transmission seems possible (i.e., four fiber spans of 80 km at a power penalty not to exceed 1 dB). It must be stressed again here that the focus of this work is the design methodology; thus, the quoted path reach (i.e., 320 km) is not absolute and will vary depending on several other parameters. In [4], it was shown that variation of PDG between 0.5 (best) and 1.5 dB (worst) and noise figure [to a worst case of 8.25 dB (maximum gain polarization) and 9.75 dB (minimum gain polarization)] will result in maximum reach variation of two spans (i.e., 160-km worst versus 320-km best). Other effects such as dispersion/chirp and gain flatness variations will further impact reach although reported results on SOA-hybrid amplifiers show flat gain (to within 0.9 dB) for wavelengths other than 1550 nm (see [3] and references therein). A 70-nm relatively flat gain bandwidth window is possible for metro applications. Inclusion of the above effects and variability studies are part of our future work.

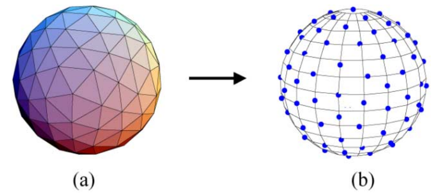

Fig. 3. (a) Tessellating the Poincare sphere creates nonoverlapping triangular grids; (b) mapping the grid nodes to azimuth and ellipticity produces the uniformly distributed input polarization states used in the model.

III. Statistical Simulation Model

Our previous results on maximum achievable reach of an SOA-amplified CWDM system were based on a worst-case assumption that signal polarization is aligned to the minimum amplifier gain axis through the entire SOA cascade. For a systems designer to provide more meaningful component design specifications for a probabilistic effect such as amplifier PDG, a statistical analysis is needed. A simple simulation-based technique was created to produce the required statistics. We first need to adequately cover the surface of the Poincare sphere with possible input signal polarization states. A constellation of approximately equidistant p points is *a priori* selected to evenly and sufficiently cover the Poincare sphere. The optimal configuration of p points on the surface of a sphere can be computed using various optimization algorithms (see [5] and the references therein). For the current work, an algorithm that uses a regular dodecahedron object is used. Each object face is subdivided into five regular triangles and each triangle is further subdivided into four smaller triangles by joining the midpoints of its sides [Fig. 3(a)]. The resulting $p = 122$ vertices are radially projected on the surface of a circumscribed sphere of unit radius. The projection points are the vertices of spherical triangles of approximately equal surface (called spherical tessellations) and are interpreted as the tips of unit Stokes vectors representing the possible orientations of the input signal polarization [see Fig. 3(b)]. To determine the OSNR penalty probability density function (pdf) for a cascade of n SOAs requires 122^n simulations.

The observation that the model of Fig. 3(b) has cylindrical symmetry with isopenalty regions on the Poincare sphere, as shown in Fig. 4(a), simplifies the problem. In one representation for example, Point A on sphere S_1 is chosen to align with the maximum gain polarization through the first SOA. Thus, a

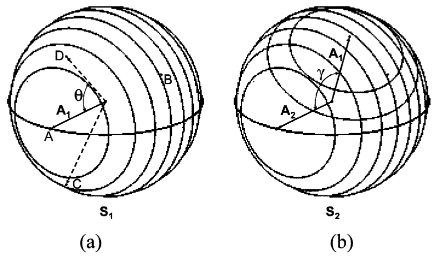

Fig. 4. (a) Isopenalty regions for one SOA and one fiber span; (b) polarization evolution (in this case rotation of the sphere) as signal goes through fiber and subsequent SOAs creates superimposed isopenalty regions.

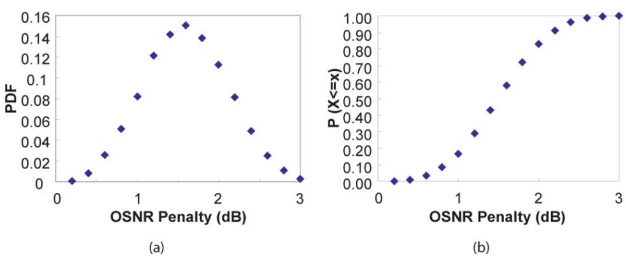

Fig. 5. (a) Polarization-induced OSNR-penalty pdf for the case of three SOAs or 320 km of path reach; (b) OSNR-penalty cdf for the same case.

signal with input polarization state corresponding to Point A in Fig. 4(a) experiences minimum penalty through the first SOA. Consequently, for the orthogonal polarization state represented by Point B, the signal will experience maximum penalty (polarization aligned to the SOA minimum gain); Points C and D belong to the same isopenalty region and experience the same penalty. Each input polarization state point of Fig. 3(b) can be easily defined by an angle θ in Fig. 4(a). This is the angle between the signal polarization vector and the SOA polarization vector (denoted by vector A_1). Once the isopenalty regions on sphere S_1 are calculated by evaluating the OSNR penalty through the first fiber span and SOA and choosing an appropriate band resolution [0.1-dB band resolution in Fig. 4(a)], the 122 points are placed on the sphere and their penalties read from the isopenalty regions. Signal passage through each subsequent fiber span and SOA simply involves rotation of A_1 (and the sphere it defines, in this case S_1) by an angle γ (derived from the tessellation of Fig. 3(b) by moving among the 122 starting points) and superposition of the isopenalty regions. This translation produces sphere S_2 (for two SOAs), as shown in Fig. 4(b). The problem of calculating the OSNR-penalty pdf through the SOA cascades then becomes simple addition of penalties as read from the superimposed isopenalty regions of spheres S_1, $S_2, \ldots, S_N$.

IV. Results

Fig. 5(a) presents the polarization-induced OSNR-penalty pdf for the case of four spans (or three cascaded SOAs) having a maximum OSNR penalty of 3 dB and minimum penalty of 0 dB. OSNR statistics can be generated by subtracting this polarization-induced OSNR penalty from the appropriate value of maximum OSNR read from the results of Fig. 2 (for four spans, the maximum OSNR is 28.2 dB [solid square]). Fig. 5(b) presents the cumulative distribution function (cdf) for the above pdf. It is clear from these results that for a "five 9's" system

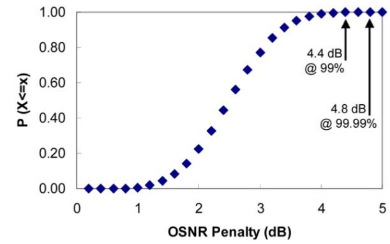

Fig. 6. Polarization-induced OSNR-penalty cdf for the case of five SOAs or 480 km of path reach.

design requirement (99.999%), we still need to add the SOA PDG in a worst-case scenario and a four-span transmission (320 km) is possible with little or no margin (see Fig. 2). Fig. 6 presents the cdf for the case of five cascaded SOAs, which does not meet the system performance requirements in Fig. 2, but has a significantly longer cdf tail (the probability increases from 99% to 100% over approximately 0.6 dB). Thus, although our method gives useful insight into system performance, only scenarios with longer amplifier cascades will produce distributions with long enough tails to permit non-worst-case specifications. For example, SOA-amplified DWDM systems, which benefit from SOAs with low PDG over a narrower optical band and a reduced OSNR requirement, should be able to take advantage of this statistical approach to gain performance margin.

It must be noted here that importance sampling could be used to achieve improved accuracy in calculating the tails of the cdfs of Fig. 6. The derivation of an analytical model for the OSNR-penalty pdfs is the focus of our current work on the above subject.

V. Conclusion

In this letter, we present an engineering design methodology for the use of cascaded SOA-based amplifiers in CWDM that focuses on the impact of PDG on the performance. The above can be of importance as CWDM systems mature and expand towards metro regions. A system and statistical model is used to understand performance and derive system requirements. As this letter focuses on OSNR requirements, degradations due to chromatic dispersion and chirp are beyond its scope. Most current generation directly modulated, unstabilized CWDM transmitters would require dispersion compensation to cover the system distances that this letter investigates.

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