PERFORMANCE ASSESSMENT OF DISPERSION-SUPPORTED TRANSMISSION AT 10- AND 20-Gb/s USING A TRAVELLING-WAVE BOOSTER AMPLIFIER

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ABSTRACT

In this paper, we assess the performance of dispersion-supported transmission at 10- and 20-Gb/s using an EDFA or a SOA as a booster amplifier. It is shown that at 10-Gb/s the use of a SOA as a booster amplifier improves the system performance for link lengths ranging from 12 to 50 km, due to partial chirp compensation in the SOA. At 20-Gb/s, the use of a SOA as a booster amplifier improves the system performance for link lengths ranging from 5 to 10 km, and degrades the system performance between 1.1 and 3.1 dB for link lengths ranging between 15 and 40 km. At 50 km the sensitivity degradation is about 4 dB.

1. INTRODUCTION

Erbium-doped fibre amplifiers are today the best choice for linear amplification, especially for in-line amplification, where polarization independence and low noise are key issues for cascading. However, the maximum span length of high bit rate optical transmission systems operating in the 1550 nm window can be severely limited by chromatic dispersion if standard single-mode fiber (SMF) are used. Without optical dispersion compensation, optical transmission at 20-Gb/s using external modulation in the 1550 nm window of SMF is dispersion limited to about 20 km [1]. The span length can be increased by using the method of dispersion-supported transmission (DST) [2], which is very attractive due to its simplicity, reliability, easiness of operation and low cost. For regenerator spacings of about 40-50 km, the use of semiconductor optical amplifiers (SOAs) may also became attractive due to their low cost, easy fabrication process, yield, reliability and compatibility with standard low cost packing techniques [3]. They have also the capability to compensate partially the laser chirp in optical transmission systems using directly modulated lasers [4]-[5]. In [4], it was shown that the chirp reduction capability of a SOA allows link lengths larger than 200 km at 4.8-Gb/s with an eye closure penalty less than 3 dB.

In this paper, we compare the performance of DST systems operated at 10- and 20-Gb/s using an erbium doped fiber amplifier (EDFA) or a SOA as a booster amplifier. Performance implications of partial chirp compensation due to self-phase modulation in SOAs, for DST systems, are also discussed. For the preamplifier we consider here an EDFA, but a SOA may also be considered if a sensitivity degradation arising from gain saturation and higher noise figure is allowed.

The remainder of this paper is organized as follows. Section 2 describes a modeling and simulation methodology for optical transmission systems using directly modulated lasers and optically preamplified direct-detection receivers. The performance assessment of DST systems operated at 10- and 20-Gb/s are presented in section 3. The main conclusions are presented in section 4.

2. SIMULATION METHODOLOGY

The block diagram of the simulated DST system is shown in Fig. 1, and a brief description of the system model follows. The pseudo-pattern generator (PPG) provides a maximal-length pseudo-random binary sequence (PRBS) with 2^7-1 bits. Assuming the laser driver behaves as a non-ideal current source, the NRZ drive current applied to the laser is generated with exponential rising and falling edges. For
modeling and simulation of the dynamic response of multi-quantum-well (MQW) lasers, a rate equation model [6]-[7] for MQW lasers has been used, which takes into account carrier transport effects. This model describes the carrier dynamics in the quantum wells and in the separate confinement heterostructure (SCH) layers, and the photon dynamics in the laser cavity, yielding the following set of equations written in terms of volumetric densities:

\[ \frac{dN_b}{dt} = \frac{I}{qV_w} - \frac{N_b}{\tau_{cap}} - \frac{N_b}{\tau_n} + \frac{N_b}{\tau_{esc}}, \quad (1) \]

\[ \frac{dN_w}{dt} = \frac{N_b}{\tau_{cap}} - \frac{N_w}{\tau_{esc}} - \frac{N_w}{\tau_n} - g_0 \frac{N_w - N_{0w}}{1 + \varepsilon S} S, \quad (2) \]

\[ \frac{dS}{dt} = \Gamma g_0 \frac{N_w - N_{0w}}{1 + \varepsilon S} S - \frac{S}{\tau_{np}} + \Gamma \beta_{sp} \frac{N_w}{\tau_n}, \quad (3) \]

\[ \frac{d\phi}{dt} = \frac{\alpha}{2} \Gamma g_0 (N_w - N_{wr}) + (1 - \Gamma) \beta_{sp} \frac{V_w}{V_s} (N_b - N_{br}), \quad (4) \]

with

\[ N_b = N_s \frac{V_s}{V_w}, \quad (5) \]

where \( N_b \) is a fictitious density, \( N_s \) is the carrier density in the SCH, \( N_w \) is the carrier density in the quantum wells, \( S \) is the photon density in the laser cavity, \( \phi \) is the phase of the optical field, \( I \) is the injection current, \( q \) is the electronic charge, \( N_{wr} \) is the carrier density in the quantum wells for the reference bias level, \( N_{br} \) is the fictitious density corresponding to the carrier density in the SCH for the reference bias level, and the other symbols are defined in table I. Some lasers exhibit a strongly non-linear light versus current characteristic above threshold due to thermal effects. Such effects have been taken into account by expressing the bimolecular recombination lifetime, \( \tau_n \), as [7]-[8]:

\[ \tau_n = \tau_{n0} e^{-K_T I_0}, \quad (6) \]

where \( \tau_{n0} \) and \( K_T \) are defined in table I and \( I_0 \) is the laser mean input current.

The laser parameters used for simulation of DST systems at 10-Gb/s are given in [8]. The laser parameters, used in simulations at 20-Gb/s, have been obtained by numerical fitting the small signal IM response of our model to measured IM responses of a strained layer MQW laser [9], using the Levenberg-Marquardt method [10]. The set of MQW laser parameters used for simulation of DST systems at 20-Gb/s are listed in table I.

Table I. MQW Intrinsic Laser Parameters

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of the quantum wells (( V_w ))</td>
<td>10.92 ( \mu )m(^3)</td>
</tr>
<tr>
<td>Volume of the SCH (( V_s ))</td>
<td>43.68 ( \mu )m(^3)</td>
</tr>
<tr>
<td>Optical confinement factor (( \Gamma ))</td>
<td>0.114</td>
</tr>
<tr>
<td>Spontaneous emission factor (( \beta_{sp} ))</td>
<td>3.38 ( \times 10^{-4} )</td>
</tr>
<tr>
<td>Differential gain in the wells (( g_0 ))</td>
<td>4.1 ( \times 10^{-12} ) m(^3)/s</td>
</tr>
<tr>
<td>Parameter of the SCH (( g_b ))</td>
<td>4.17 ( \times 10^{-13} ) m(^3)/s</td>
</tr>
<tr>
<td>Carrier density at transparency (( N_{0w} ))</td>
<td>1.06 ( \times 10^{24} ) m(^{-3})</td>
</tr>
<tr>
<td>Bimolecular recombination lifetime at a reference temperature (( \tau_{n0} ))</td>
<td>0.7393 ns</td>
</tr>
<tr>
<td>Transport time across the SCH (( \tau_{cap} ))</td>
<td>5.068 ps</td>
</tr>
<tr>
<td>Thermionic emission time out (( \tau_{esc} ))</td>
<td>384.56 ps</td>
</tr>
<tr>
<td>Photon lifetime (( \tau_p ))</td>
<td>0.5097 ps</td>
</tr>
<tr>
<td>Gain compression factor (( e ))</td>
<td>2.95 ( \times 10^{-23} ) m(^3)</td>
</tr>
<tr>
<td>Linewidth enhancement factor (( \alpha ))</td>
<td>3</td>
</tr>
<tr>
<td>Differential quantum efficiency per facet (( \eta ))</td>
<td>0.0442</td>
</tr>
<tr>
<td>Thermal constant (( K_T ))</td>
<td>13.222</td>
</tr>
<tr>
<td>Emission wavelength (( \lambda_0 ))</td>
<td>1550 nm</td>
</tr>
</tbody>
</table>

Erbium doped fiber amplifiers (EDFAs) have been considered as linear with an equivalent noise bandwidth of 1 THz and a noise factor of 6 dB. A SOA is assumed to be used as a booster amplifier, instead of an EDFA, in order to investigate the influence of gain saturation and partial chirp compensation on the performance of DST systems. By using the approximation in which the internal loss is much smaller than the gain, the pulse propagation in SOAs can be described as [11]:

\[ ]
\begin{align*}
P_{\text{out}}(t) &= P_{\text{in}}(t)e^{G(t)}, \quad (7) \\
\phi_{\text{out}}(t) &= \phi_{\text{in}}(t) - \frac{1}{2} \alpha_H G(t), \quad (8) \\
\frac{dG(t)}{dt} &= \frac{G_0 - G(t)}{\tau_c} - \frac{P_{\text{in}}(t)}{E_{\text{sat}}}[e^{G(t)} - 1], \quad (9)
\end{align*}

where $P_{\text{in}}(t)$ and $\phi_{\text{in}}(t)$ are the power and the phase of the input optical field, respectively, $P_{\text{out}}(t)$ and $\phi_{\text{out}}(t)$ are the power and the phase of the output optical field, respectively, $G(t)$ represents the integrated gain at each point of the pulse profile, $e^{G_0}$ is the unsaturated single-pass gain of the amplifier, and $E_{\text{sat}}$ is the saturation energy, $\tau_c$, is the carrier lifetime, and $\alpha_A$ is the linewidth enhancement factor.

The following SOA parameters have been used in the simulations: $\tau_c=100$ ps, $\alpha_A=5$, $E_{\text{sat}}=5$ pJ, and $10\log(e^{G_0})=20$ dB.

![Diagram](image.png)

Fig. 1. Block diagram of the simulated DST system.

The standard single-mode fiber (SMF) was modeled using the low-pass transfer function with first order dispersion of 17ps/(nm.km) at 1550 nm. The PIN photodiode, the receiver main amplifier (AMP), and the low-pass filter (LPF) have been jointly modeled as a low-pass RC filter with the 3-dB bandwidth required by the DST method.

For performance evaluation, a pure semi-analytical method has been used, which combines noiseless signal transmission simulation with noise analysis in optical transmission systems using directly modulated MQW lasers and optically preamplified direct-detection receivers. Using the Gaussian approximation, the average error probability may be estimated by [12]:

\[ P_e = \frac{1}{L} \sum_{k=1}^{L} Q \left( \frac{v(\tau_k)-V_{th}}{\sigma_k} \right), \quad (10) \]

with

\[ Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-\frac{y^2}{2}} \, dy, \quad (11) \]

where $L$ is the length of the used PRBS, $v(\tau_k)$ is the value of the signal voltage at the sampling instant $\tau_k$, $V_{th}$ is the decision threshold level, and $\sigma_k$ is the standard deviation of the noise voltage for the $k$th bit of the PRBS, which is given by:

\[ \sigma_k^2 = \sigma_{s-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{sh}^2 + \sigma_{th}^2 + \sigma_{ld}^2, \quad (12) \]

where $\sigma_{s-sp}^2$ is the variance of the signal-ASE beat noise voltage, $\sigma_{sp-sp}^2$ is the variance of the ASE-ASE beat noise voltage, $\sigma_{sh}^2$ is the variance of the shot noise voltage, and $\sigma_{th}^2$ is the variance of the thermal noise voltage, and $\sigma_{ld}^2$ is the voltage due to the laser noise after the receiver filter. The optical amplifier noise model we use here is based on the model originally derived for semiconductor optical amplifiers [13], and further extended to fiber amplifiers [14]-[15]. The signal photocurrent, $I_{k}$, is obtained by simulation and signal dependent noise terms are evaluated for each bit of the PRBS. Being $I_{sp}$ the spontaneous emission noise photocurrent given by [15]:

\[ I_{sp} = \frac{\eta q}{h\nu} n_{sp}(G-1)h\nu B_{\nu} L_{\alpha}, \quad (13) \]

the variance of the noise voltage terms are given by:
\[ \sigma_{s-sp}^2 = 2Z_R^2 I_k I_{sp} \frac{B_e}{B_o}, \]  
\[ \sigma_{s-p-sp}^2 = Z_R^2 I_{sp}^2 \frac{B_e}{B_o} \left( 1 - \frac{B_e}{2B_o} \right), \]  
\[ \sigma_{sh}^2 = 2B_e q Z_R^2 \left[ I_k + I_{sp} \right], \]  
\[ \sigma_{th}^2 = Z_R^2 I_{th}^2 B_e, \]  
\[ \sigma_{ld}^2 = I_k^2 Z_R^2 \int_0^\infty S_{out}(\omega) |H_R(\omega)|^2 d\omega, \]  

where \( B_e \) is the electrical bandwidth, \( B_o \) is the optical bandwidth, \( \eta \) is the quantum efficiency of the PIN photodiode, \( q \) is the electronic charge, \( h \) is Planck's constant, \( v \) is the optical frequency, \( G \) is the optical preamplifier gain, \( L_a \) is the loss between the optical preamplifier output and the photodetector input, \( n_{sp} \) is the spontaneous emission factor of the EDFA, \( Z_R \) is the receiver transimpedance, and \( I_{th} \) is the spectral current density of the thermal noise, which is assumed to be 10 pA/\( \sqrt{\text{Hz}} \). \( H_R(\omega) \) is the receiver transfer function and \( S_{out}(\omega) \) is the intensity noise power spectral density at the fiber output given in [16].

### 3. PERFORMANCE ASSESSMENT

For each fiber length, the system parameters, namely the bias current, the modulation current, and the receiver cut-off frequency have been adjusted in order to minimize the EDFA preamplifier input mean optical power for an average error probability (BER) of \( 10^{-9} \) (receiver sensitivity).

Fig. 2 shows the receiver sensitivity versus fiber length for DST at 10-Gb/s assuming that an EDFA or a SOA is used as a booster amplifier. As can be seen, if a SOA is used instead of an EDFA, the system performance is improved, due to partial chirp compensation in the SOA, for link lengths ranging from 12 to 50 km SMF. For link lengths larger or equal than 80 km the system performance is degraded at least 1.4 dB. Thus, for DST systems operated at 10-Gb/s, the use of a SOA for short length applications may became desirable.

![Fig. 2. Receiver sensitivity for DST at 10-Gb/s versus fiber length assuming that an EDFA or a SOA is used as a booster amplifier.](image1)

Fig. 3 shows the receiver sensitivity versus fiber length for DST at 20-Gb/s assuming that an EDFA or a SOA is used as a booster amplifier.

![Fig. 3. Receiver sensitivity for DST at 20-Gb/s versus fiber length assuming that an EDFA or a SOA is used as a booster amplifier.](image2)
degradation ranges between 1.1 and 3.1 dB. At 50 km SMF the sensitivity degradation is about 4 dB.

4. CONCLUSIONS

The performance of DST systems operated at 10- and 20-Gb/s have been assessed assuming that an EDFA or a SOA is used as a booster amplifier. It is shown that the use of a SOA as a booster amplifier in 10-Gb/s DST systems improves the performance for link lengths ranging from 12 to 50 km SMF, due to partial chirp compensation. These results make SOAs attractive for short length applications. However, for 20-Gb/s DST systems the use of a SOA improves the system performance only for link lengths ranging from 5 to 10 km, and degrades the system performance between 1.1 and 3.1 dB for link lengths ranging between 15 and 40 km SMF. At 50 km SMF the sensitivity degradation is about 4 dB.

5. REFERENCES