Evaluate the Performance of Optical Time Division Demultiplexing with the Gain Saturation effect of Semiconductor Optical Amplifier

Bobby Barua, *Member, IACSIT and IEEE*

***Abstract*— Optical Time Division Multiplexing (OTDM) system technique is the extend time division multiplexing by optically combining a number of lower speed electronic baseband digital channels. In addition, the Semiconductor Optical Amplifiers (SOA's) are important components for optical networks. In this paper, we propose a novel model for an OTDM demultiplexer based on Cross Gain Modulation in a SOA. Analysis are extended to find the output of an optical IM/DD receiver to receive the demultiplexed optical signal and to find the output signal to noise ratio (SNR) taking into account the amplified spontaneous emission (ASE) noise. The results are evaluated in terms of BER, SNR and pump power for various input signal power level. It is found that, at a given signal input power the BER can be reduced by increasing the pump power and the required pump power is higher at higher level of input power.**

***Index Terms*—Cross Gain Modulation, Gain Saturation effect, Optical Time Division Multiplexing (OTDM), Semiconductor Optical Amplifiers (SOA's).**

I. INTRODUCTION

Optical amplifiers have become increasingly important in modern optical communication systems. Semiconductor Optical Amplifiers (SOA's) are important components for optical networks [1-5].. In the linear regime, they can be used for both booster and in-line amplifiers in the 1.3 μm window. On the other hand, potential use of SOA's nonlinearities for all-optical signal processing has led to research in various application fields. One application is demultiplexing of optical time division multiplexed (OTDM) signal using a SOA as a nonlinear element in a short fiber loop, a configuration also known as terahertz optical asymmetric demultiplexer (TOAD) [1] or semiconductor laser amplifier in a loop mirror (SLALOM) [2]. The gain in a semiconductor optical amplifier saturates as the optical power level increases. Therefore, it is possible to modulate the amplifier gain with an input signal, and in turn, encode this gain modulation on a separate continuous-wave (CW) probe signal travelling through the amplifier at another wavelength [3]. If a pump signal with high enough intensity is coupled into a SOA, the whole spectrum of the amplifier's spontaneous emission (ASE) output will be modulated due to the cross gain modulation (XGM) effect. That means, while the ASE spectrum will be in low level if the pump signal is in high level, the ASE spectrum will be in high level if the pump signal is in low level [4]. The potential of SOA's has led to the development of various theoretical models [5]. A time-domain amplifier model based on the gain (and index) dynamics and taking into account the spectral profile has been reported [6]. The model is suitable for investigating and optimizing the performance of a SOA in a system environment. The latest 400-Gbit/s transmission experiments based on optical signal processing are presented and the possibility of terabit/second TDM transmission is discussed [7]. A theoretical model which takes into consideration amplifier gain dynamics and pulse propagation describes the demultiplexing experiments and predicts the device performances also at higher bit rates [8]. In Ref. [9] A. A. M. Saleh et al. showed that the nonlineanty inherent in semiconductor optical amplifiers can cause adverse system effects, such as intermodulation distortion (IMD) in FDM systems, crosstalk in on/off-keying WDM systems, and pulse distortion in multi-Gbit/s on/off keying systems. A practical, feed-forward linearization scheme that is capable of reducing these effects significantly is presented. A two-tone experiment confirms the reduction of the IMD by about 14dB. Again an analytic expression for the channel gains of a traveling-wave amplifier is used to discuss and compare the crosstalk for ASK and FSK systems [10]. The relatively short carrier lifetime in high-gain amplifiers may ultimately limit the channel spacing of such multichannel systems. C. Joergensen, et al. [11] experimentally analyzed that semiconductor optical amplifiers are used for efficient wavelength conversion up to 4 Gb/*s*. The rise and fall time as well as extinction ratio are. System performance at 4 Gb/s is evaluated showing a penalty of only 1.5 dB for the converted signal for conversion over 17 nm. T. Durhuus et al. [12] presented an in depth analysis of cross gain and cross phase wavelength conversion in semiconductor optical amplifiers. The cross gain modulation scheme shows extinction ratio degradation for conversion to longer wavelengths. The first results for monolithic integrated interferometric wavelength converters are reviewed, and the quality of the converted signals is demonstrated by transmission of 10 Gb/s converted signals over 60 km of nondispersion shifted single mode fiber. In this paper we try to develop an analytical model for cross-gain modulation in a SOA operating in the saturation region and to use this XGM effect to demultiplex an optical channel from the input optical time division multiplexed bit stream. Based on the analytical model we further extend our analysis in the time domain to find the demultiplexed optical signal at the output of the SOA and to find the expression for the signal spectrum at the output. In addition to find the signal power, inter-channel crosstalk power as well as the efficiency of demultiplexing for a given input bit rate and number of OTDM channels. The analysis will also include

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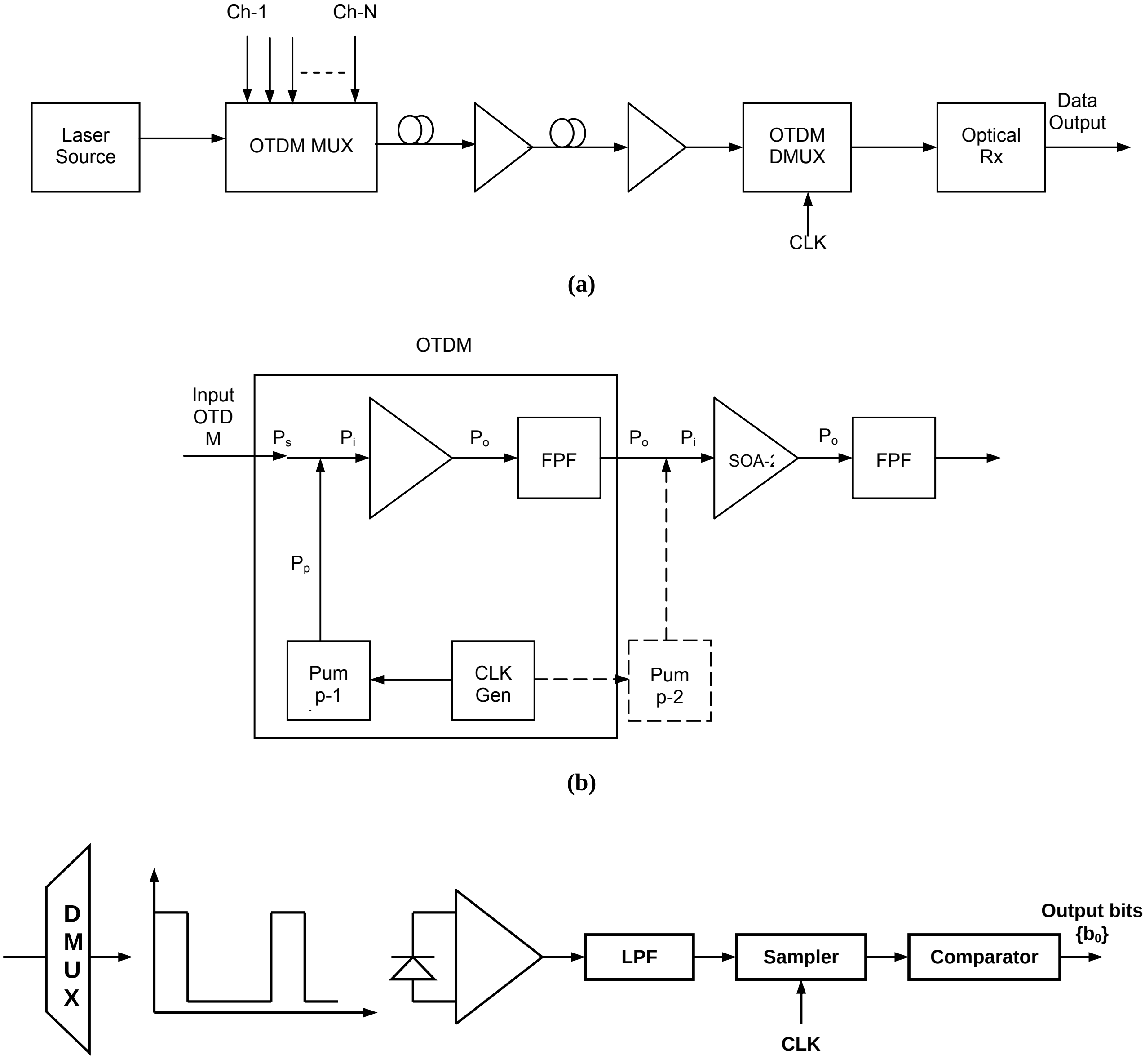
Bobby Barua is with Department of EEE, Ahsanullah University of Science and Technology, Dhaka, Bangladesh. (Email: bobby@aust.edu).

the effect of optical amplifier's spontaneous emission (ASE) noise optical filters following SOA-based OTDM demultiplexer. Finally, the impact of inter-channel crosstalk on the bit error rate (BER) performance of an OTDM transmission system will be determined. The outcome of this research is expected to provide an analytical approach for designing an OTDM system using SOA-based demultiplexer.



(a)

(b)

(c)

Fig.1. (a): Block diagram of an OTDM transmission system. (b): Block diagram of an OTDM demultiplexer based on SOA (c): Block diagram of a direct detection optical receiver

II. SYSTEM MODEL

The block diagram of an OTDM transmission system is shown in Fig.1.(a) The block diagram of the proposed OTDM demultiplexer based on SOA is shown in Fig.1(b). Here two Semiconductor Optical Amplifier stages are used for theoretical analysis. The input OTDM signal is mixed with the pump signal of pump laser-1 and is fed to the SOA-1. The presence of the pump power causes the SOA-1 to go to the saturation which results in a low gain of the SOA-1. The pump is driven by the clock signal from a clock generator to select the desired OTDM channel. When the clock is high, the SOA-1 goes to saturation and the output goes to lower level, otherwise the output remains high. Thus during the desired channel slot time, the output of SOA-1 is low if a bit '1' is present in the time slot. If the bit is '0', the SOA-1 does not go to saturation and the output remains high. Thus the output of the SOA-1 is high for a '0' bit in the desired channel slot and is low for a '1' bit in the desired channel slot. The output of SOA-1 is given input to SOA-2 which acts as an inverter as it goes to saturation giving low output for a '1' bit (high) input and remains at higher output level for a '0' input bit (low input level) due to gain saturation effect caused by the input power level. The pump power of SOA-2 is selected to adjust the total input power of the amplifier to achieve gain saturation corresponding to high input power level. The output of the OTDM demultiplexer is given input to an optical direct detection receiver to receive the transmitted data bits of the desired channel. The output signal of the OTDM DMUX is fed to a direct detection optical receiver. The block diagram of the receiver is shown in Fig.1.(b). The receiver optical signal at the output of the OTDM Demultiplexer is given by:

$$r(t) = E_s(t) + E_{sp}(t) \qquad (1)$$

where, $E_s(t) = \sqrt{2P_2}\, e^{j\omega_c t}$, for '1' bit (2)

$= \sqrt{2P_1}\, e^{j\omega_c t}$, for '0' bit

e optical amplifiers in cascade.

III. PERFORMANCE ANALYSIS OF THE OTDM DEMULTIPLEXER

The OTDM signal can be represented as:

$$E_s(t) = \sqrt{2P_s}\sum_{j=0}^{\infty}\sum_{k=0}^{N-1} a_{k,j}\, p(t - kT_b - jT_F) \times e^{j\omega_c t} \qquad (3)$$

where, $\{\alpha_{k,j}\} = \{0,1\}$, N is the number of OTDM channels, $\alpha_{k,j}$ is the k-th bit of the j-th OTDM frame. P_s is the average optical signal power of the OTDM channel. The pump signal given input to SOA-1 at nth time slot is given as:

$$E_{p1}(t) = \sqrt{2P_{p1}}\sum_{j=0}^{\infty} p(t - jT_F - nT_b) \times e^{j\omega_p t} \qquad (4)$$

n is the channel index to be demultiplexed = {0, N-1} and ω_p is the angular frequency of the pump laser with power P_{p1}.

The total power input signal given to SOA-1 is then given by

$$E_{in1}(t) = E_s(t) + E_{p1}(t) \qquad (5)$$

Total input to the SOA-1 is then given by:

$$P_{in1} = P_s + P_{p1} \qquad (6)$$

The electric field at the output of SOA-1 is given by:

$$E_{o1}(t) = [\sqrt{2G_1(t)P_s}\sum_{j=0}^{\infty}\sum_{k=0}^{N-1} a_{k,j}\, p(t - kT_b - jT_F) + \sqrt{2G_1P_{p1}}\sum_{j=0}^{\infty} p(t - jT_F - nT_b)] \times e^{j\omega_c t} \qquad (7)$$

where, ($\omega_c = \omega_p$), $a_{k,j}$ represents k-th bit of the j-th OTDM frame, and P_{p1} is the pump power of the pump laser-1 corresponding to the n-th bit of the j-th frame.

The instantaneous gain of the SOA-1 depends on the input power level and can be expressed as:

$G_1(t) = G_1$ for k = n, $a_k = +1$
$= G_2$ for k = n, $a_k = 0$
$= G_2$ for k ≠ n

For $a_{n,j} = +1$

$$E_{o1}(t) = \sqrt{2G_1(P_s + P_{p1})}\sum_{j=0}^{\infty} a_{k,j}\, p(t - nT_b - jT_F) \times e^{j\omega_c t} \qquad (8)$$

If G_s represents the single pass gain, then $G_1 < G_s$, $G_2 = G_s$

For $a_{n,j} = 0$, $E_{o1}(t) = \sqrt{2G_2P_{p1}} \times e^{j\omega_c t}$ (9)

and $E_{sp}(t)$ is the spontaneous emission noise of th
For n ≠ k, $G_{11} < G_{12}$ and $G_1 < G_2$,

$$E_{o1}(t) = \sqrt{2G_2P_s}\sum_{j=0}^{\infty}\sum_{\substack{k=0\\k\neq n}}^{N-1} a_{k,j}\, p(t - kT_b - jT_F)e^{j\omega_c t} \quad ,(0<t<T_F) \qquad (10)$$

$G_1 << G_2 = G_s$, so that $G_1(P_s + P_{p1}) < G_2P_{p1n}$

So output $P_{o1} = G_1(P_s + P_{p1})$ (11)

$$P_{o2} = G_2P_{p1} \qquad (12)$$

As $G_2 >> G_p$, $P_{o2} > P_{o1}$

So the dynamic range and the extinction ratio of the demultiplexed signal at the output of SOA-1 can be represented as:

$$\text{Dynamic Range} = \text{DR} = P_{o2} - P_{o1} \qquad (13)$$

$$\text{Extinction Ratio} = \varepsilon = P_{o1}/P_{o2} \qquad (14)$$

The demultiplexed signal of the output of SOA-1 is fed to the input of SOA-2 with pump input power P_{p2}. The input signal to the SOA-2 is given by:

$$E_{in2}(t) = E_{01}(t) + E_{p2}(t) \qquad (15)$$

where, $E_{01}(t)$ is given by equation (8), (9), (10) and (11) and $E_{p2}(t)$ is the electric field input to SOA-2 from the pump laser-2 and is given by:

$$E_{p2}(t) = \sqrt{2P_{p2}}\sum_{n=0}^{\infty} p(t - jT_F - nT_b)e^{j\omega_c t} \qquad (16)$$

The output signal of the SOA-2 is then given by:

$$E_{o2}(t) = \sqrt{2[G_1(P_s + P_{p1}) + P_{p2}]} \times \sqrt{G_{21}}\sum_{j=0}^{\infty} p(t - jT_F - nT_b)e^{j\omega_c t} \qquad (17)$$

where, G_{21} is the gain of SOA-2 corresponding to low input power level.

For k = n and $a_k = +1$

$$E_{02}(t)=\sqrt{2G_2(P_{p1}+P_{p2})}\times\sqrt{G_{22}}e^{j\omega_c t} \qquad (18)$$

for k = n and $a_k = 0$

$$E_{02}(t)=\sqrt{2[G_1(P_s+P_{p1})+P_{p2}]}\times\sqrt{G_{22}}\sum_{n=0}^{N-1}\sum_{j=0}^{\infty}P(t-jT_F-nT_b)e^{j\omega_c t} \qquad (19)$$

where, G_{22} on the gain of the SOA-2 corresponding to high levels of the input signal and $G_{22}<G_{21}$.

Thus output power levels of SOA-2 are:

$$P_1 = 2[G_1(P_s+P_{p1})+P_{p2}]G_{21} \text{ for ‘1’ bit} \qquad (20)$$

$$P_0 = 2(G_2P_{p1}+P_{p2})G_{22} \text{ for ‘0’ bit} \qquad (21)$$

If the total optical field is the sum of the signal field E_s and the spontaneous emission field E_{sp}, then the total photo detector current i_{tot} is proportional to the square of the electric field of the optical signal,

$$i_{tot}\propto\left(E_s+E_{sp}\right)^2=E_s^2+E_{sp}^2+2E_sE_{sp} \qquad (22)$$

Here the first two terms arise purely from the signal and noise respectively. The third term is a mixing component i.e. a beat signal between the signal and noise, which can fall within the bandwidth of the receiver and degrade the signal to noise ratio.

The mean signal currents corresponding to ‘1’ or ‘0’ bits are given as:

$$I_{s1}=\Re.P_1 \text{ and } I_{s0}=\Re.P_0$$

Considering ASE noise, and neglecting dark current noise, the total shot noise current is given by [3],

$$\left\langle I_{shot}^2\right\rangle=\sigma_{shot}^2=\sigma_{shot-s}^2+\sigma_{shot-sp}^2=2qB_e(I_{s1}+I_{sp}) \text{ - ‘1’}$$

(23)

$$=2qB_e(I_{s0}+I_{sp}) \qquad \text{ - ‘0’}$$

where, $I_{s1}=\Re.P_1$, $I_{s0}=\Re.P_0$ and $I_{sp}=\Re.P_{sp}$, $\Re$ is the responsivity of the photodiode, G is the amplifier gain and $P_{sp} = n_{sp}(G-1)h\nu B_0$, n_{sp} is the spontaneous emission factor and $h\nu$ is the photon energy.

The other two noises arise from the mixing of the different optical frequencies contained in the light signal and the ASE, which generates two sets of beat frequencies. Since the signal and the ASE have different optical frequencies, the beat noise of the signal with the ASE is [3],

$$\sigma_{s-sp}^2=4(\Re GP_{in})(\Re P_{sp}\frac{B_e}{B_0}) \qquad (24)$$

In addition, since the ASE spans a wide optical frequency range, it can beat against itself giving rise to the noise current as [3],

$$\sigma_{sp-sp}^2=(\Re P_{sp})^2B_e\frac{(2B_0-B_e)}{B_0^2} \qquad (25)$$

The total noise variance at the output of the receiver LPF is given by:

$$\sigma^2=\sigma_{th}^2+\sigma_{shot-s}^2+\sigma_{shot-sp}^2+\sigma_{s-sp}^2+\sigma_{sp-sp}^2 \qquad (26)$$

The noise variance corresponding to a ‘1’ bit is given by:

$$\sigma_1^2=\sigma_{th}^2+2qB_e(I_{s1}+I_{sp})+4(\Re GP_1)(\Re P_{sp}.\frac{B_e}{B_0})+\sigma_{sp-sp}^2 \qquad (27)$$

and that corresponding to a ‘0’ bit is given by:

$$\sigma_o^2=\sigma_{th}^2+2qB_e(I_{so}+I_{sp})+4(\Re GP_o)(\Re P_{sp}.\frac{B_e}{B_o})+\sigma_{sp-sp}^2 \qquad (28)$$

The signal to noise ratio (SNR) at the output can be expressed as:

$$SNR=\frac{I_{s1}-I_{s0}}{\sigma_1+\sigma_o} \qquad (29)$$

The extinction ratio (ER) is then given by,

$$\varepsilon=\frac{I_{s0}}{I_{s1}} \qquad (30)$$

The bit error rate (BER) can be expressed as [1-3],

$$BER=0.5erfc\left\lfloor\frac{SNR}{\sqrt{2}}\right\rfloor \qquad (31)$$

In most cases of practical interest, thermal noise dominates receiver performance, i.e. $\sigma_{th}^2 >> \sigma_{shot}^2$ [1-3]. Neglecting the shot noise terms in SNR becomes,

$$SNR=\frac{(\Re GP_{in})^2}{2qB_e\Re P_{cross}+\frac{4kTB_eF_n}{R_L}} \qquad (32)$$

When the receiver performance is dominated by shot noise, i.e. $\sigma_{shot}^2 >> \sigma_{th}^2$ and $\sigma_1^2 >> \sigma_0^2$, the SNR becomes,

$$SNR=\frac{(\Re GP_{in})^2}{2qB_e\Re\left(GP_1+P_{sp}+P_{cross})+4(\Re GP_1)(\Re P_{sp}\frac{B_e}{B_0})+(\Re P_{sp})^2B_e\frac{(2B_0-B_e)}{B_0^2}+\frac{4kTB_eF_n}{R_L}\right)}$$

(33)

In a multiple span system, where N numbers of amplifier are cascaded, the crosstalk power (P_{cross}) and the spontaneous emission power (P_{sp}) in (32) is to be replacement by NP_{cross} and NP_{sp} respectively in order to obtain cumulative effect of crosstalk and amplified spontaneous noise.

IV. RESULTS AND DISCUSSION

Following the theoretical analysis presented in section III, we evaluate the performance results of an OTDM demultiplexer based on gain saturation effect at different bit rates and system parameters. System parameters used for computation are shown in the table 1.

TABLE1: SYSTEM PARAMETERS USED FOR COMPUTATION

Parameter Name	**Typical Value**
Bit Rate, R_b	5 ~ 25 Gbps
Temperature, T	300° K
Fiber attenuation, α	0.24 dB/Km
Responsivity, $\Re$	0.85 A/W
Current intensity, I_{th}	10×10^{-12} ampere
Load resistance, R_L	50 ohm
Gain, G_1	20 dB
Gain, G_2	10 dB
Boltzman constant, k	1.38×10^{-23}
Electron charge, e	1.602×10^{-19} coulombs

Other results are presented in terms of signal to noise ration (SNR) and bit error rate (BER) and extinction ratio at the output of the demultiplexer followed by a direct detection receiver. The variation of the gain of SOA with input power obtained by simulation is depicted in Fig.2. It shows that as the input power increases, the gain of the amplifier goes towards saturation. This characteristic of the SOA is used for demultiplexing a channel from an OTDM signal.

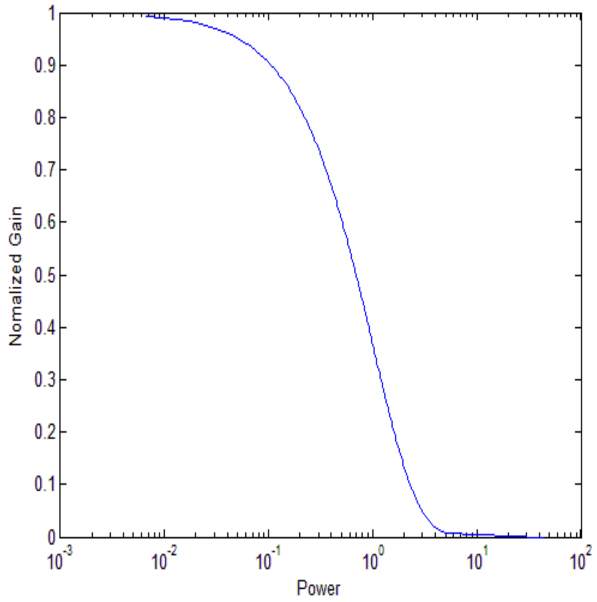


Fig. 2: Gain vs. input power Pin (dBm) of a SOA

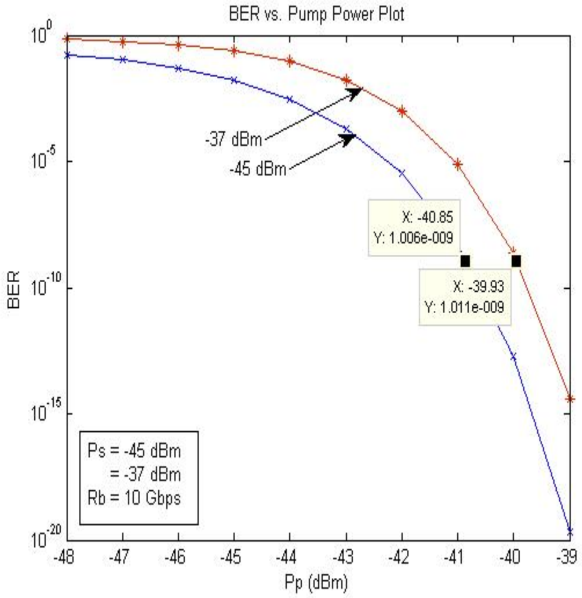


Fig. 3. Plots of BER vs. pump power, P_p(dBm) of an OTDM transmission link with a direct detection receiver at the output of OTDM DMUX at a bit rate of 10 Gbps with signal power P_s as a parameter

The plots of BER of the OTDM system versus pump power of SOA-1 are depicted in Fig.3 for signal power Ps = -45 dBm and -37 dBm. It is noticed that the bit error rate decreases with increase in pump power at a given signal power level. At higher signal power level the BER is higher. The receiver sensitivity in terms of P_p(dBm) at a BER of 10^{-9} is found to be -40.85 dBm and -39.93 dBm corresponding to P_s = -45 dBm and -37 dBm respectively. It is clearly found that the required values of P_s(dBm) are within the normal operational range of signal levels in a direct detection receiver.

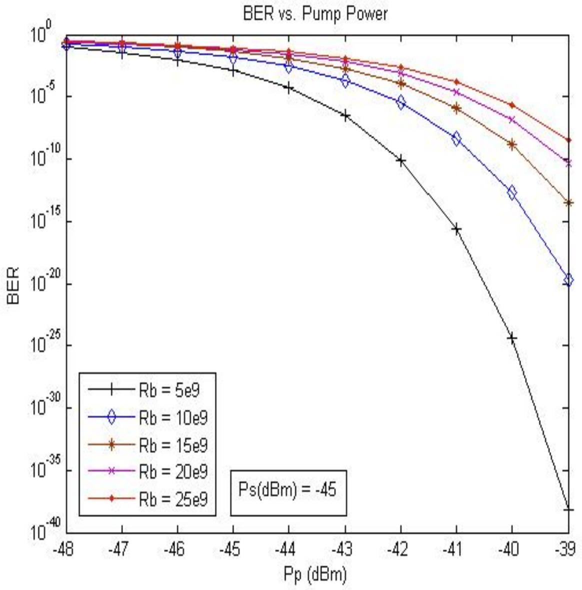


Fig.4. Plots of BER vs. pump power, P_p(dBm) of an OTDM transmission link with a direct detection receiver at the output of OTDM DMUX at a signal power P_s = -45 dBm with bit rate as a parameter

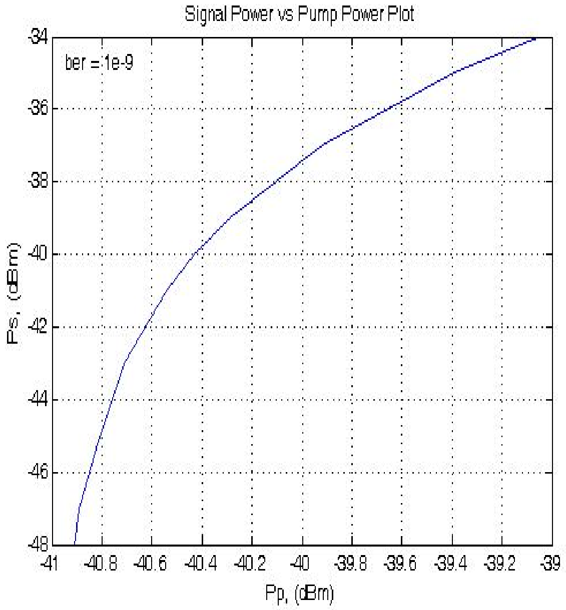


Fig.5. Plots Signal power vs. pump power at BER = 10^{-9} and R_b = 10Gbps

Fig.4 depict the plots of BER versus pump power of SOA-1 with bit rate R_b as a parameter. The plots are shown for R_b = 5 Gbps to 25 Gbps for P_s = -80 dBm, -70 dBm and -45 dBm respectively. The plots reveal that at increased bit rate, the required pump power is higher to achieve a specific BER (say, 10^{-9}). Thus the required receiver sensitivity is higher at higher bit rate due to increased receiver noise.

The relationship between the required value of P_s(dBm) to achieve a given BER of 10^{-9} corresponding to a given P_p(dBm) is depicted in Fig.5 for operation at a bit rate of 1Gbps. It is clearly found that the required values of P_s(dBm) are within the normal operational range of signal levels in a direct detection receiver.

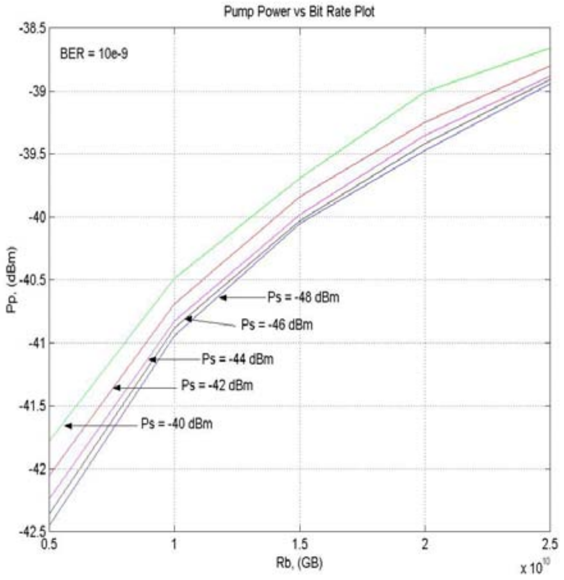


Fig.6. Plots of pump power versus bit rate at a BER = 10^{-9} with signal power as a parameter (varying from -48 to -40 dBm)

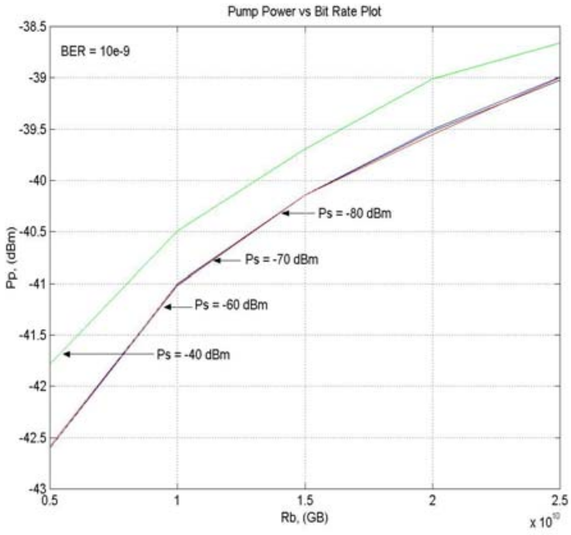


Fig.7. Plot of pump power versus bit rate at a BER = 10^{-9} with signal power as a parameter (varying from -40 to -80 dBm).

The plots of required receiver sensitivity in terms of P_p(dBm) as a function of R_b are shown in Fig.6. and Fig.7. with P_s as a parameter corresponding to BER = 10^{-9}. It is noticed that the required value of P_s(dBm) is higher at high bit rate at BER = 10^{-9} due to increased value of P_p(dBm). The Fig.6. shows the results for smaller range of values of P_s and Fig.7. shows the results for higher values of P_s

The dependence of extinction ratio at the output of the OTDM DMUX with pump power of SOA-1, P_p(dBm) is depicted in Fig.8. at a bit rate of 5 Gbps at a BER = 10^{-9} with P_s(dBm) as a parameter. The figure clearly depicts how the degradation in extinction ratio occurs at higher values of signal power P_s(dBm) due to gain saturation effect of SOA. This is due to the fact that at higher signal power input, the dynamic range between the signal levels for ‘1’ and ‘0’ bits is reduced. At low input signal power, there is a significant improvement in extinction ratio.

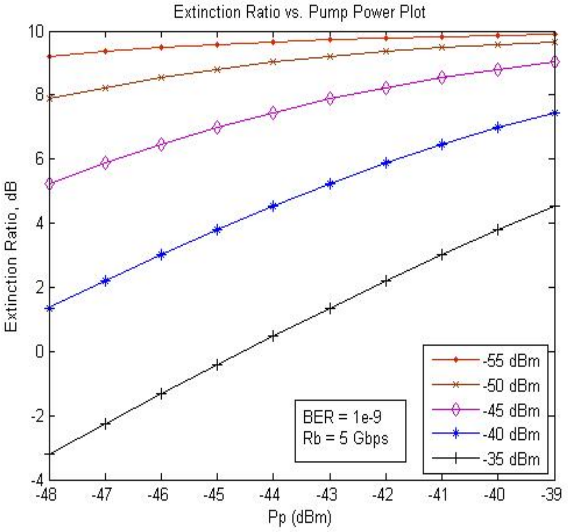


Fig.8. Plot of extinction ratio versus pump power at R_b = 5 Gbps, BER = 10^{-9} with signal power as a parameter (varying from -35 to -55 dBm)

V. CONCLUSIONS

A model is developed for an OTDM demultiplexer based on Cross Gain Modulation (XGM) in a Semiconductor Optical Amplifier (SOA). The performance of the OTDM demultiplexer is evaluated in terms of output signal corresponding to '0' and '1' bit of the desired OTDM channel. Expression is developed for the output signal current and noise currents when an optical Direct Detection (DD) receiver used to receive the demultiplexed signal. The expression for Signal to Noise Ratio (SNR) and Extinction Ratio (ER) and Bit Error Rate (BER) are also derived. It is noticed that the bit error rate decreases with increase in pump power at a given signal power level. At higher signal power level the BER is higher. For instance the receiver sensitivity in terms of P_p(dBm) at a BER of 10^{-9} is found to be -40.85 dBm and -39.93 dBm corresponding to $P_s = -45$ dBm and -37 dBm respectively. It is clearly found that the required values of P_s(dBm) are within the normal operational range of signal levels in a direct detection receiver. The relationship between the required value of P_s(dBm) to achieve a given BER of 10^{-9} corresponding to a given P_p(dBm) is determined for operation at a bit rate of 5 Gbps. The figure clearly depicts how the degradation in extinction ratio occurs at higher values of signal power due to gain saturation effect of SOA.

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