Semiconductor Optical Amplifiers in WDM Tree-Net

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Abstract—In this paper, effectiveness of semiconductor optical amplifiers (SOA's) in tree-net in terms of increase in the number of users has been investigated. In the analysis, SOA's with i) unsaturated gain, ii) average gain saturation, and iii) average gain saturation with gain fluctuations have been considered. Further, the results for the tree-net are compared with those for the star network. It is observed that tree-net supports more number of users than star for a given number of SOA's.

Index Terms—Optical amplifiers, tree-net, wavelength division multiplexed networks.

I. INTRODUCTION

THE ever-increasing demand for high capacity networks has led to the wavelength division multiple access (WDMA) fiber optic networks. Packet switched services can also utilize other multiple access techniques, i.e., code division multiple access (CDMA) and time division multiple access (TDMA) to provide high capacities, but these are relatively difficult to implement in optical domain. WDM packet switched networks can be implemented on various topologies e.g., star, ring, bus, tree etc. Among these topologies, star can support maximum number of users (typically, 64 users) [1]. Supportable number of users can be increased by using semiconductor optical amplifiers (SOA's). In star networks, required number of SOA's is same as the number of users [1]. In the tree-net, there is a possibility of sharing the SOA's amongst users. Hence, tree-net may be able to support more users as compared to star for a given number of SOA's.

In this paper, placement of SOA's in tree-net topology has been investigated. The tree-net with and without SOA's has been analyzed. Subsequently, a comparative study of the tree-net and a star network has been made.

II. SYSTEM MODEL

The tree-net topology is a two-level topology; main topology being star and auxiliary one, the folded bus [2]. In this topology, the number of users, N_u, can increase as $2^i n$ where i is an integer and n the number of users per branch. There will be $b (= 2^i)$ number of branches. The topology is illustrated in Fig. 1 for $n = 4$ and $b = 4$. The users marked "1" are first-order users and the ones marked "2" are second-order users and so on. Therefore, order of users varies from one to n. The users are connected to folded bus segments through 3 dB 2×2 couplers. The star-portion (above dotted line in Fig. 1) also uses 3 dB 2×2 couplers. The loss in the above network
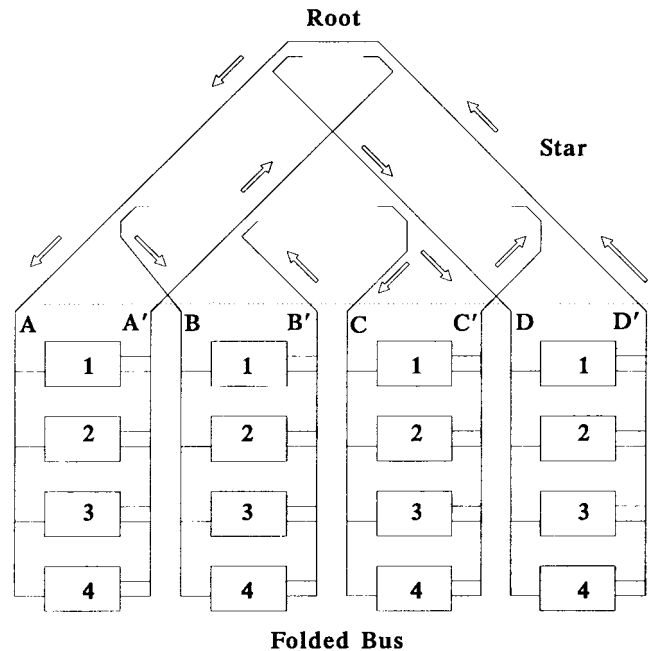
Fig. 1. Basic tree-net topology.

can be reduced by realizing star portion as a multistage star coupler [3].

In tree-net topology, $2^k (k = 0, 1, 2, 3 \cdots)$ number of SOA's can be used. There are three cases for incorporating SOA's in the tree-net, viz. i) N_a is one (2^0), ii) N_a is less than b, and iii) N_a is equal to b. These configurations are shown in Fig. 2(a), (b), and (c), respectively, for 4×4 star-portion of a tree-net. In general, when N_a amplifiers are to be incorporated, a multistage star coupler of dimension $N_a \times N_a$ is needed which is realized using 3 dB 2×2 couplers. The amplifiers are attached at the output of this star coupler. The dimension of the resulting star coupler is increased to $b \times b$ using 3 dB 2×2 couplers for power splitting and combining at the output and input, respectively. The above star coupler with SOA's is assumed to be made on a single substrate using integrated optic techniques. Therefore, amplifier coupling loss has been considered to be negligible in the analysis.

In the following analysis, number of wavelength channels in the tree-net are assumed to be b. Further, all the users in each branch transmit on the same wavelength. It is also assumed that each transmitter in the tree-net adjusts its transmitter power such that the power received from its own transmitter is same as received from highest order user. Thus, a farthest (highest order) user from the root on the bus transmits maximum power. This implies that the optical power level at the amplifier input in each channel is same.
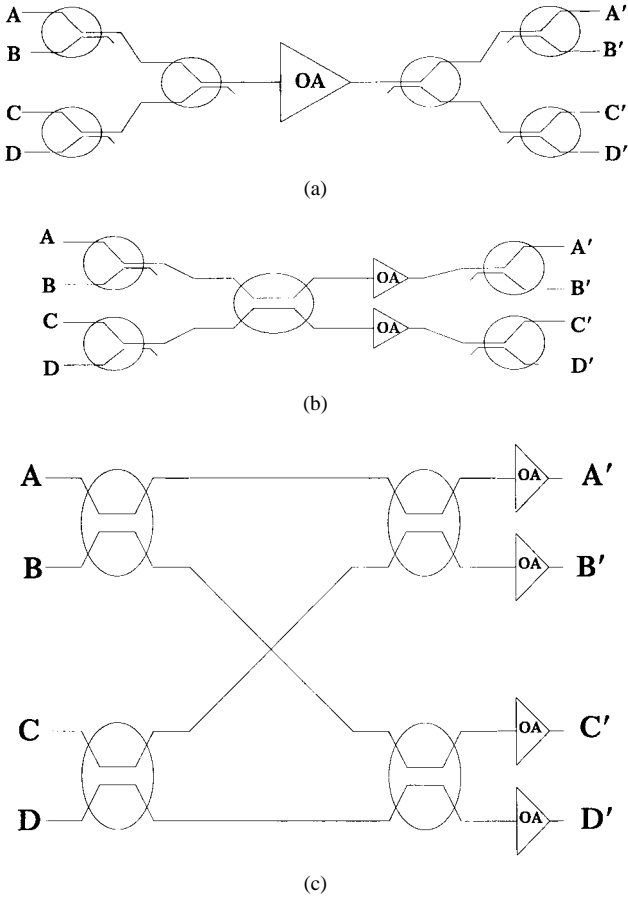
Fig. 2. Star-coupler with (a) one amplifier, (b) two amplifiers, and (c) four amplifiers in tree-net.

A. Optical Amplifier

The SOA's are considered in the analysis as these are better suited for system integration. Gain of these amplifiers reduces with the increase in input optical power level. This is referred to as gain saturation. The saturated gain G of the amplifier is obtained by solving the following nonlinear equation [4]:

$$G = G_0 \exp\left(-[G-1]\frac{P_{\text{in}}}{P_{\text{sat}}}\right) \qquad (1)$$

where G_0 is the unsaturated gain, P_{in} the total input optical power, P_{sat} the saturation power level. The G_0 and P_{sat} are the amplifier parameters. The SOA's, in addition to amplified signals, also produce amplified spontaneous emission (ASE) noise. This noise degrades the system performance. The single sided power spectral density, S_{sp}, of ASE noise at the amplifier output is given by [4]

$$S_{\text{sp}} = n_{\text{sp}}[G-1]h\nu \qquad (2)$$

where n_{sp} is spontaneous emission noise factor, h the Planck's constant, and ν the frequency of optical carrier. At the photodetector, the ASE noise beats with signal and itself to produce ASE-signal and ASE-ASE beat noise components. When ASE noise beats with itself, it also produces a dc signal which is responsible for additional shot noise component [5].

In multichannel WDM systems, the amplifier gain for a given channel depends on the total input signal power and

hence bit patterns in all the channels. This results in interchannel crosstalk and termed as cross-saturation. The above give rise to i) average gain saturation and ii) gain fluctuations. Their degrading effect is considered in the following sections.

III. ANALYTICAL MODEL

In order to analyze the effectiveness of SOA's in tree-net, following four cases are considered, i.e., tree-net i) without SOA, ii) with unsaturated SOA's, iii) with SOA's having average gain saturation, and iv) with SOA's having average gain saturation and gain fluctuations. The highest order (farthest from root) transmitter has been considered for the worst-case analysis.

Analytical expressions for the evaluation of bit error rate (BER) for all the above cases are derived in Appendix A [1]. In the derivation, various losses are required which are described below. In the tree-net without SOA's, the loss L_{TR} between transmitter and receiver is given by

$$\begin{aligned} L_{TR} &\quad (\text{in dB}) \\ &= 2(n-1)L_{ss}\alpha + (n-1)(L_i+3) + 2\alpha L + 4L_{\text{sp}} \\ &\quad + (L_i+3)\log_2 b + (L_i+3)(n-1) + L_{FI} \qquad (3) \end{aligned}$$

Here, L_{ss} is the fiber loss between two consecutive users on a bus, L_i the insertion loss of a 3 dB 2×2 coupler, α the attenuation coefficient of fiber in dB/km, L the length of fiber between order one user and star portion of the network in km, L_{sp} the splice loss and L_{FI} the insertion loss of filter or wavelength demultiplexer at the receiver. The received optical power level is determined from the transmitter power level and the loss L_{TR}. The noise variances at receiver (due to shot and thermal noises) are determined for received optical power levels for bit 1 and 0. The BER which equalizes the probability of error for bit 1 and 0 is computed using the signal currents and noise variances (see the Appendix).

In case of unsaturated SOA's, the input power level to the amplifier in a channel is determined from the transmitter power level and the loss L_{TA} between transmitter and amplifier. This loss is given by

$$\begin{aligned} L_{TA} &\quad (\text{in dB}) \\ &= (n-1)L_{ss}\alpha + (n-1)(L_i+3) + \alpha L + 2L_{\text{sp}} \\ &\quad + (L_i+3)\left\{\log_2\left(\frac{b}{N_a}\right) + \log_2(N_a)\right\}. \qquad (4) \end{aligned}$$

The received signal and ASE noise levels at the receiver of order j $(1 \leq j \leq n)$ are determined using the unsaturated gain G_0 of the amplifier and loss L_{AR} between amplifier and the receiver. This loss is given by

$$L_{AR} \quad (\text{in dB})$$
$$= \begin{cases} (L_i+3)\log_2\left(\frac{b}{N_a}\right) + \alpha L + 2L_{\text{sp}} \\ +(j-1)L_{ss}\alpha + (L_i+3)j + L_{FI} & \text{for } j < n \\ \\ (L_i+3)\log_2\left(\frac{b}{N_a}\right) + \alpha L + 2L_{\text{sp}} \\ +(j-1)L_{ss}\alpha + (L_i+3)(j-1) + L_{FI} & \text{for } j = n. \end{cases}$$
$$(5)$$

The noise variance due to ASE-signal beat noise, ASE-ASE beat noise, shot noise (due to signal and dc component of ASE-ASE beat noise) and thermal noise are determined for bit 1 and 0. The BER which equalises the probability of error for bit 1 and 0 is then determined (see the Appendix).

In the average gain saturation case, signal power at the input of SOA is determined as mentioned above. It is presumed that bits in all the channels at the input of SOA are synchronised which produces maximum degradation [6], [7]. For a given number of channels having bit 1, total input power to SOA is determined and used for finding the saturated gain. The average gain is determined by averaging this gain over the binomial distribution of number of channels having bit 1. The received optical signal and ASE noise at the receiver are determined using this average gain. These are used to obtain the signal levels and noise variances which in turn determine the BER (Appendix A).

In the last case, i.e., tree-net with SOA's having average gain saturation and gain fluctuations, the BER is averaged using distribution of channels having bit 1. For a given channel, the power level at the input of a SOA is determined as in the case of tree-net with unsaturated SOA's. For a given number of interfering channels with bit 1, the saturated gain of SOA for bit 1 and 0 in the desired channel is determined. Then received optical signal power and ASE noise psd are determined at the receiver input. These are used for determining signal levels and noise variances for bit 1 and 0 in the desired channel at the receiver output. As there are $(b - 1)$ interfering channels, b signal levels for both bit 1 and 0 will exist depending upon the number of interfering channels having bit 1. The highest signal level for bit 0 is always less than the lowest level for bit 1 [6]. Using these two levels, threshold is determined which equalises the probability of error for these levels. The probability of error for each signal level is determined using the corresponding noise variance and the computed threshold. This probability of error is averaged for equiprobable bit 1 and 0 in the desired channel and the binomial distribution of number of interfering channels (Appendix A).

IV. EXAMPLE

The effectiveness of SOA's on a sample tree-net is studied using the above model. The unsaturated gain G_0 of SOA's is in the range of 8–29 dB; P_{sat} in the range 3.1–15.6 dBm. The noise figure for SOA's ranges from 6 to 8.5 dB which corresponds to n_{sp} of 2–3.5 [8], [9], [10], [11]. The parameters selected for the sample tree-net are given in Table I. Table II shows the number of users supported, N_u, and minimum required transmitter power level, P_T (dBm), for various values of n in the tree-net without SOA's. Variations of N_u with N_a for tree-net with i) unsaturated SOA's, ii) average gain saturated SOA's, and iii) average gain saturated SOA's with gain fluctuations are shown in Figs. 3, 4, and 5, respectively. Numbers shown in brackets are the minimum required P_T (dBm) for the corresponding values of N_u and N_a. For example, in Fig. 3(a) when $n = 2$ and $N_a = 32$, P_T is -5.4 dBm and corresponding N_u is 512. It is remarked that plot for

TABLE I
SAMPLE TREE-NET PARAMETERS

Maximum allowed transmitter power	0 dBm
Desired BER	10^{-9}
Insertion loss of 2x2 coupler, L_i	0.5 dB
Unsaturated gain of SOAs, G_o	29 dB
Saturation power level, P_{sat}	10 dBm
Distance between the root and first order node on a branch, L	1 km
Distance between consecutive nodes on a branch, L_{ss}	100 m
Fiber attenuation coefficient, α	0.2 dB/km
Receiver load resistance, R_L	100 Ω
Operating wavelength, λ	1.55 μm
Optical BW of a passband in wavelength demultiplexer, B_u	10 GHz
Electrical bandwidth of receiver, B_e	1 GHz
Receiver temperature, T	300 °K
Spontaneous emission factor, n_{sp}	3.0
Splice insertion loss, L_{sp}	0.5 dB
Insertion loss of wavelength demultiplexer, L_{fi}	0.5 dB
Extinction ratio, ε	0.10

TABLE II
NUMBER OF USERS SUPPORTED N_u AND
REQUIRED P_T FOR TREE-NET WITHOUT SOA's

Number of users per branch (n) *	Tree-net without SOAs	
	$N_u = bn$	P_T (dBm)
1	64	-2.2
2	32	-2.2
3	12	-1.8

*   For $n \geq 4$, no users can be supported with $P_T \leq 0$ dBm.

$n = 1$ (not shown here) are similar to the ones for $n = 2$. It is observed that for a given value of n, increase in N_a may result in increased N_u or reduced P_T or both. Increase in N_a does not necessarily increase N_u. Since in tree-net N_u varies in discrete steps, the next higher value may not be supported if the required P_T is above 0 dBm. For example, N_u is 192 for $n = 3$ and $N_a = 4$ [Fig. 3(b)]. When the N_a is increased to 8, N_u is still 192 because for the next admissible number $N_u = 384$, required P_T is greater than 0 dBm. But the next higher value of N_a i.e., 16 results in increase of N_u to 384. It is noticed that increase in N_a from 4 to 8 results in reduction in P_T from -2.6 to -5.7 dBm and no change in N_u. Therefore, $N_a = 8$ is not useful as the available P_T is 0 dBm and there is no increase in N_u.

When average gain saturated SOA's are considered, a decrease in N_u is observed compared to the above. For example, when $n = 2$, $N_a = 16$ supports 512 users for unsaturated SOA's and 256 users for average gain saturated SOA's. This behavior is true for all values of n. Further, the gain fluctuations in SOA's either increase P_T or reduce N_u. For example, when $n = 2$, $N_a = 16$ still supports same number of users as in average gain saturation case, but P_T has increased to -2.6 dBm from -3.8 dBm showing a power penalty of 1.2 dB. An example of reduction in N_u is $n = 3$, $N_a = 8$ when N_u reduces from 192 to 96 [see Figs. 4(b) and 5(b)].

In tree-net topology, $n = 3$ provides the values of N_u which are not admissible in star topology. This is advantageous in certain cases as seen in Table III. The table shows the values of N_u in all the three cases corresponding to each N_a. For each case, minimum required P_T has also been computed
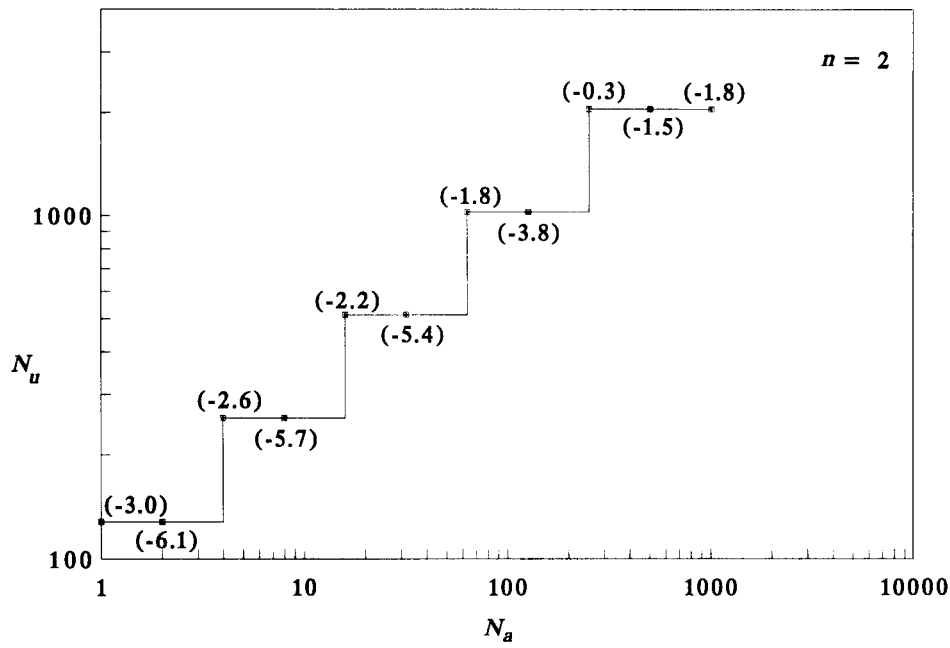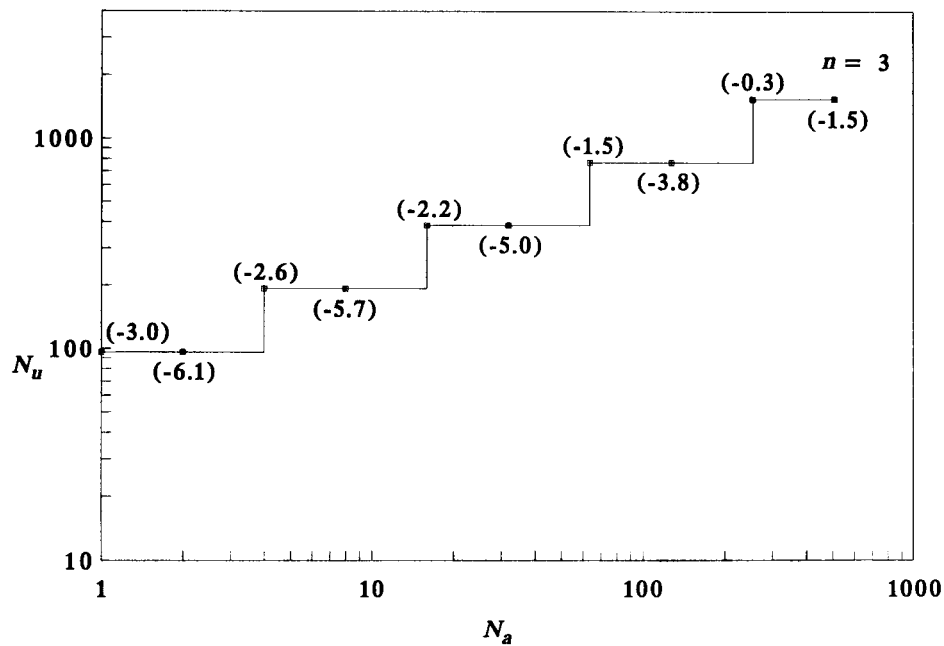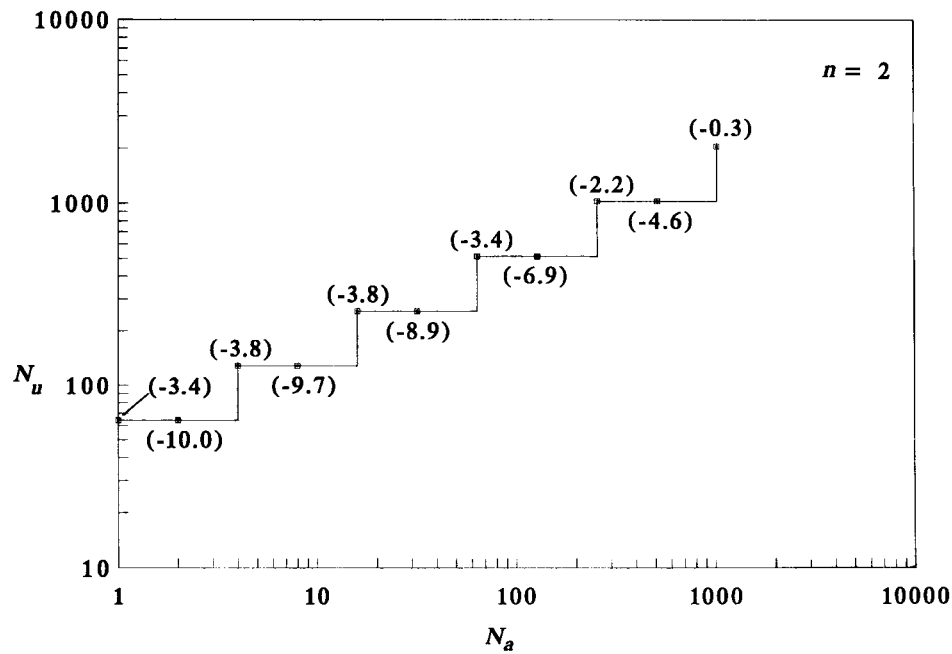
Fig. 3. Variations of N_u with N_a (unsaturated amplifiers) for (a) $n = 2$ and (b) $n = 3$. The values in the brackets are corresponding required P_T in dBm.

and shown. It is observed that maximum number of users are supported by $n = 2$ in most of the cases. The worst-case losses in $n = 1$ and 2 are almost same, but the required number of wavelengths in $n = 2$ are halved. This results in reduced effect of average gain saturation and fluctuations. In some cases, $n = 3$ supports more number of users than $n = 2$ (e.g., $N_a = 32$ supports a maximum of 384 users for $n = 3$ in average gain saturation case). This is due to the peculiarity of number of users admissible in the tree-net for $n = 3$.

A comparison of tree-net with star network is given in Table IV. It is observed from this table that both the networks can support 64 users without SOA's. Both star network and tree-net with SOA's can support 128 users. However, the former needs 128 SOA's and the latter 4 SOA's. Similarly, star network can support 256 users and 512 users with 256 and 512 SOA's respectively, while the tree-net requires 16 and 64 SOA's to support the same number of users, respectively. It is also observed that 1024 users are supported by the tree-net only. The above is possible as the amplifiers are integrated within the star coupler and the amplifier coupling loss is negligible. Therefore, the tree-net requires lesser number of SOA's for a given number of supportable users. Both star

(a)
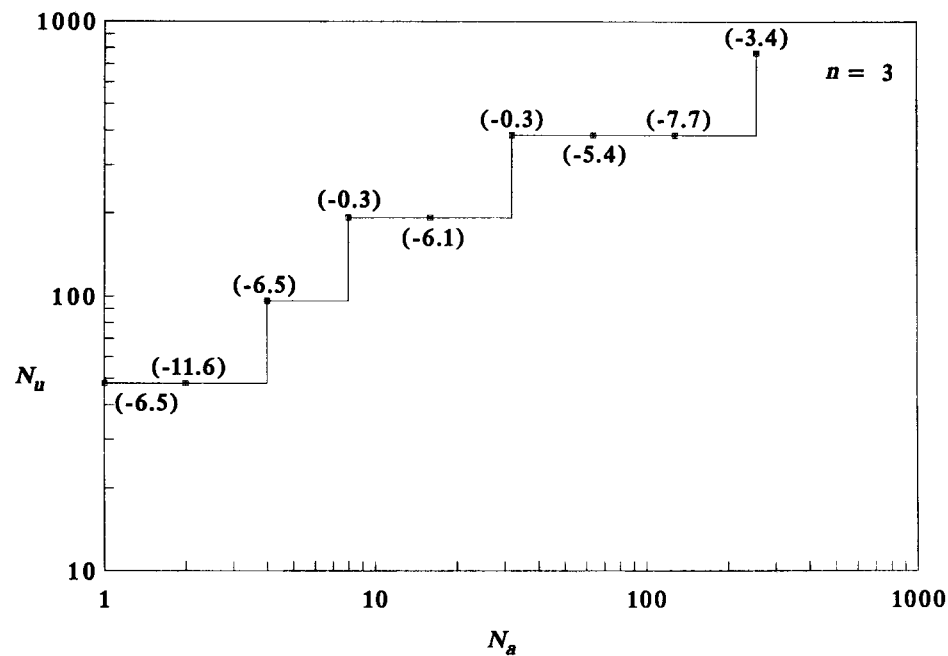
(b)

Fig. 4. Variations of N_u with N_a (average gain saturated SOA's) for (a) $n = 2$ and (b) $n = 3$. The values in the brackets are corresponding required P_T in dBm.

network and tree-net cannot support more than 1024 users irrespective of number of SOA's used.

V. CONCLUSIONS

It has been observed that the gain saturation in SOA's affects the performance of the tree-net. It reduces number of users supported as compared to unsaturated SOA's. The gain fluctuations in SOA's further deteriorate the performance. Since the star topology supports maximum number of users without SOA's, star network and the tree-net are compared.

It is shown that the tree-net require lesser number of SOA's as compared to star for a fixed number of supportable users. This is because of topological advantage of the tree-net in terms of wider choices of number of users per SOA. It is remarked that in comparison to star network, tree-net offers distinct advantages in terms of more geographical coverage, less usage of fiber and transmitter sharing between more than one user [12], [13].

In this paper, crosstalk due to gain saturation, nonideal filter and demultiplexers and four-wave mixing has not been
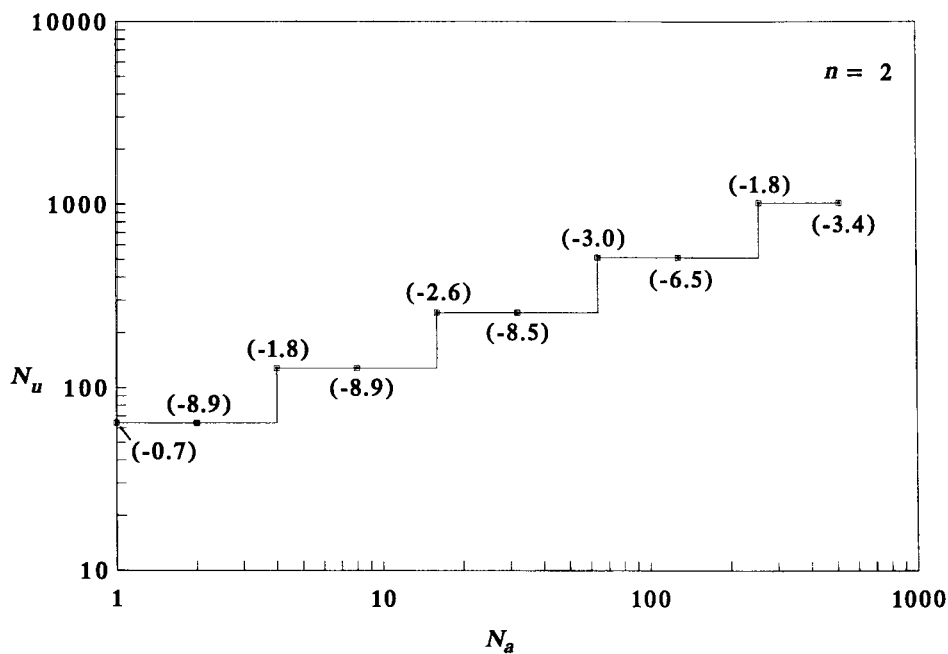
(a)
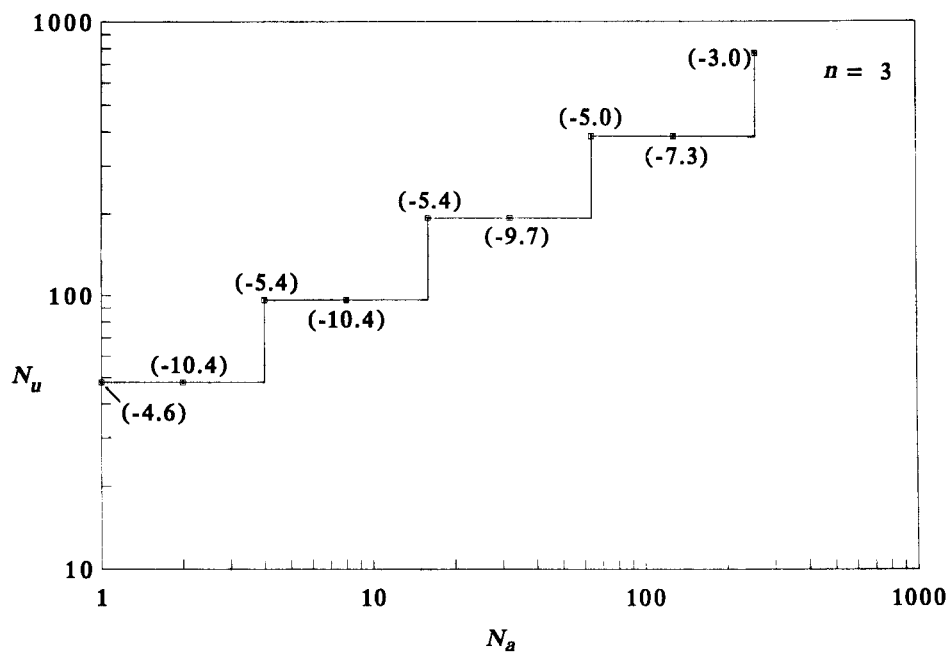
(b)

Fig. 5.   Variations of N_u with N_a (average gain saturated SOA's with gain fluctuations) for (a) $n = 2$ and (b) $n = 3$. The values in the brackets are corresponding required P_T in dBm.

considered. The optical sources are presumed to be noise free and couplers wavelength independent.

APPENDIX
EVALUATION OF BER IN TREE-NET

A. Tree-Net Without SOA's

In the tree-net without SOA's, power received at photodetector for bit i (i is either 1 or 0) is given by

$$P_R(i) = P_S(i)L_{TR} \qquad \text{(A-1)}$$

where

$$P_S(1) = \frac{2P_T}{\varepsilon + 1} \qquad \text{(A-2a)}$$

and

$$P_S(0) = \frac{2P_T \varepsilon}{\varepsilon + 1}. \qquad \text{(A-2b)}$$

In the above equations, P_T represents the average transmitter power and ε the extinction ratio.

TABLE III
MAXIMUM N_u AND P_T FOR A GIVEN N_a WHEN AMPLIFIERS
ARE i) UNSATURATED, ii) AVERAGE GAIN SATURATED, AND
iii) AVERAGE GAIN SATURATED WITH GAIN FLUCTUATIONS.
NUMBERS IN BRACKETS ARE THE CORRESPONDING VALUES OF n

Number of amplifiers N_a	Unsaturated SOAs		Average gain saturated SOAs		Average gain saturated SOAs with gain fluctuations	
	N_u (n)	P_T (dBm)	N_u (n)	P_T (dBm)	N_u (n)	P_T (dBm)
1	128 (2)	-3.0	64 (2)	-3.4	64 (2)	-0.7
2	128 (2)	-6.1	64 (2)	-10.0	64 (2)	-8.9
4	256 (2)	-2.6	128 (2)	-3.8	128 (2)	-1.8
8	256 (2)	-5.7	192 (3)	-0.3	128 (2)	-8.9
16	512 (2)	-2.2	256 (2)	-3.8	256 (2)	-2.6
32	512 (2)	-5.4	384 (3)	-0.3	256 (2)	-8.5
64	1024 (2)	-1.8	512 (2)	-3.4	512 (2)	-3.0
128	1024 (2)	-3.8	512 (2)	-6.9	512 (2)	-6.5
256	2048 (2)	-0.3	1024 (2)	-2.2	1024 (2)	-1.8
512	2048 (2)	-1.5	1024 (2)	-4.6	1024 (2)	-3.4
1024	2048 (2)	-1.8	2048 (2)	-0.3	1024 (2)	-3.0
2048	2048 (1)	-1.8	2048 (1)	-1.1	-	-

TABLE IV
COMPARISON OF STAR NETWORK AND TREE-NET HAVING
AVERAGE GAIN SATURATED SOA's WITH GAIN FLUCTUATIONS

Number of users N_u	Number of SOAs required	
	Star	Tree
64	0	0
128	128	4
256	256	16
512	512	64
1024	-	256

The signal current and noise variance for bit i ($i = 0$ or 1) at photodetector output are given by

$$I_{\text{sig}}(i) = R_o P_R(i) \tag{A-3a}$$

and

$$\sigma^2(i) = 2eR_o P_R(i)B_e + \frac{4kTB_e}{R_L} \tag{A-3b}$$

where k is the Boltzmann's constant, T the temperature in Kelvin and R_L the load resistance of the photodetector. The first term on right-hand side of (A-3b) represents the shot noise and second term the thermal noise. The average probability of error with threshold level which equalizes the BER for bit 1 and 0 is given by

$$P_e = \frac{1}{2}\text{erfc}\left(\frac{I_{\text{sig}}(1) - I_{\text{sig}}(0)}{\sqrt{2}[\sigma(0) + \sigma(1)]}\right). \tag{A-4}$$

B. Tree-Net with Unsaturated SOA's

Let the gain of unsaturated amplifier be G_0. The $P_R(i)$ at the receiver of order j is given by

$$P_R(i) = P_S(i)L_{TA}G_0L_{AR}. \tag{A-5}$$

The ASE noise psd at the receiver will be

$$S_{\text{sp}} = n_{\text{sp}}[G_0 - 1]h\nu L_{AR}. \tag{A-6}$$

The signal current and noise variance for bit i are given by

$$I_{\text{sig}}(i) = R_0 P_R(i) \tag{A-7a}$$

and

$$\sigma^2(i) = 2eR_0[P_R(i) + S_{\text{sp}}B_0]B_e + 4R_0^2 P_R(i)S_{\text{sp}}B_e + R_0^2 S_{\text{sp}}^2[2B_0B_e - B_e^2] + \frac{4kTB_e}{R_L}. \tag{A-7b}$$

Equations (A-5)–(A-7) are used to determine average P_e from (A-4).

C. Tree-Net with Average Gain Saturated SOA's

To determine the average amplifier gain, the probability distribution of number of channels having bit 1 is presumed to be binomial. Let N_1 channels out of total N channels are having bit 1. The probability that N_1 channels are having bit 1 is given by

$$P_{N1} = \binom{N}{N_1}\left[\frac{1}{2}\right]^N. \tag{A-8}$$

The input power to the amplifier corresponding to bit i is

$$P_{\text{in}}(i) = P_S(i)L_{TA}. \tag{A-9}$$

Therefore, the total input power to the amplifier is $N_1 P_{\text{in}}(1) + (N - N_1)P_{\text{in}}(0)$. The corresponding saturated gain $G(N_1)$ of the amplifier is computed using (1) with the above input power. The average gain is given by

$$G_{\text{av}} = \sum_{N_1=0}^{N} P_{N1}G(N_1). \tag{A-10}$$

The signal power received for bit i will be

$$P_R(i) = P_{\text{in}}(i)G_{\text{av}}L_{AR} \tag{A-11}$$

As G_{av} is independent of signal bit, the ASE noise psd for both bit 1 and 0 will be same. It is given by

$$S_{\text{sp}} = n_{\text{sp}}[G_{\text{av}} - 1]h\nu L_{AR}. \tag{A-12}$$

Equations (A-11) and (A-12) are used to determine signal currents ($I_{\text{sig}}(1)$ and $I_{\text{sig}}(0)$) and noise variances ($\sigma^2(1)$ and $\sigma^2(0)$) as in (A-7) Then average P_e is computed using (A-4).

D. Tree-Net with SOA's Having Average Gain Saturation and Gain Fluctuations

The probability of N_1 channels out of $N - 1$ interfering channels having bit 1 is given by

$$P'_{N1} = \binom{N-1}{N_1}\left[\frac{1}{2}\right]^{N-1}. \tag{A-13}$$

The corresponding total amplifier input power for the bit i in the desired channels is $P_{\text{in}}(i) + N_1 P_{\text{in}}(1) + (N-1-N_1)P_{\text{in}}(0)$. Therefore, the saturated gain $G(i, N_1)$ of the amplifier is computed using the above total input power as P_{in} in (1).

For bit i, the signal power and ASE noise psd at the photodetector is given by

$$P_R(i, N_1) = P_{\text{in}}(i)G(i, N_1)L_{AR} \tag{A-14a}$$

and

$$S_{\text{sp}}(i, N_1) = n_{\text{sp}}[G(i, N_1) - 1]h\nu L_{AR}. \tag{A-14b}$$

The signal current and noise variance corresponding to bit i are given by

$$I_{\text{sig}}(i, N_1) = R_0 P_R(i, N_1) \tag{A-15a}$$

and

$$
\begin{aligned}
\sigma^2&(i, N_1) \\
&= 2eR_0[P_R(i, N_1) + S_{\text{sp}}(i, N_1)B_0]B_e \\
&\quad + 4R_0^2 P_R(i, N_1)S_{\text{sp}}(i, N_1)B_e \\
&\quad + R_0^2[S_{\text{sp}}(i, N_1)]^2 [2B_0 B_e - B_e^2] + \frac{4kTB_e}{R_L}. \tag{A-15b}
\end{aligned}
$$

Both $I_{\text{sig}}(1)$ and $I_{\text{sig}}(0)$ will have N levels depending upon the value of N_1. The threshold corresponding to highest level of $I_{\text{sig}}(0)$ and lowest level of $I_{\text{sig}}(1)$ will be

$$D_{\text{th}} = \frac{\sigma(0,0)I_{\text{sig}}(1, N-1) + \sigma(1, N-1)I_{\text{sig}}(0,0)}{\sigma(0,0) + \sigma(1, N-1)}. \tag{A-16}$$

The probability of error under the condition that N_1 interfering channels are having bit 1 is given by

$$
\begin{aligned}
P_e(N_1) = \frac{1}{2}&\left[\frac{1}{2}\text{erfc}\left(\frac{I_{\text{sig}}(1, N_1) - D_{\text{th}}}{\sqrt{2}\sigma(1, N_1)} \right) \right. \\
&\left. + \frac{1}{2}\text{erfc}\left(\frac{D_{\text{th}} - I_{\text{sig}}(0, N_1)}{\sqrt{2}\sigma(0, N_1)} \right) \right]. \tag{A-17a}
\end{aligned}
$$

The average P_e will be

$$P_e = \sum_{N_1=0}^{N-1} P'_{N1} P_e(N_1). \tag{A-17b}$$

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