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Dual-Stage EDFA for Improving the Performance of Long-Haul Optical Systems

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ABSTRACT A cascade of single-stage erbium doped fiber amplifiers (SS-EDFAs) are known to improve the signal strength and system reach in long-haul optical systems. However, such a cascade introduces an amplified spontaneous emission (ASE) noise accumulation, which results in system performance degradation. To reduce this ASE noise accumulation, we propose the incorporation of a dual-stage EDFA (DS-EDFA) with a narrow bandwidth (typically 3 nm or even smaller depending on the system under consideration) bandwidth optical bandpass filter (OBPF) in the system. We analyze the role of a DS-EDFA, which is formed using two identical SS-EDFAs, for its effectiveness in improving the overall system performance. The gain vs input power characteristic comparison is provided for the DS-EDFA (without interstage OBPF) modelled in OptSim and MATLAB. A system-level numerical model in MATLAB matching the OptSim parameters has been presented to validate the OptSim results. For a cascade incorporating DS-EDFA with interstage OBPF, a system-level analysis is presented with results obtained from a simulated model designed using OptSim. The results demonstrate the effectiveness of DS-EDFA in improving the optical signal-to-noise ratio (OSNR) and bit error rate (BER) performance of the long- haul optical system under consideration. From the obtained results, the optimum placement of a DS-EDFA at the start of the amplifier chain/cascade is recommended for practical implementation in a long-haul optical communication system.

INDEX TERMS EDFA, gain saturation, noise figure, ASE noise, OSNR monitoring, BER, optical bandpass filter.

I. INTRODUCTION

Erbium doped fiber amplifier (EDFA) have been deployed in fiber–optics communication (FOC) system, to boost the signal strength and increase the transmission distance of the signal. Although EDFAs have readily replaced electrical repeaters and made the optical-electrical-optical (OEO) conversion process obsolete [1], their internal amplified spontaneous emission (ASE) noise contributes to degrading the optical-signal-to-noise ratio (OSNR) of the system. The ASE noise occurs due to the spontaneous emission of photons during the amplification mechanism of an EDFA. The noise figure (NF) value provides a fair measure of the OSNR degradation due to this ASE noise [2].

A notable characteristic of EDFAs is its gain reduction when the incident power exceeds a certain threshold - known as the input saturation power [2]. Generally, an EDFA delivers better performance compared to a semiconductor optical amplifier (SOA), especially in the saturation regime of operation [2]. Additionally, the degree of signal distortion occurring in a saturated SOA is worse compared to a saturated EDFA [2], [3]. Apart from EDFA and SOA, Raman fiber amplifier (RFA) is also used in optical networks, as it offers a wider bandwidth. However, when concerned with long-haul C-band communication, EDFAs are generally preferred over RFAs given their low cost, high pump power utilization, good gain stability and high gain characteristics [4]. For the above reasons the work presented here will only focus on EDFAs.

The optical signal present at the output of an EDFA incorporates the ASE noise component along with the amplified input signal. While using a narrow-band optical filter in the system can reduce ASE noise to a degree, some research suggests altering the internal mechanism of an EDFA and varying the erbium ion concentration (to achieve higher gain for shorter fiber length) can further minimize the ASE noise [5]. However, when a series of EDFAs are cascaded, the ASE

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noise builds up as it propagates through the successive EDFAs in the system and the accumulated ASE noise at the optical receiver input severely affects the system performance.

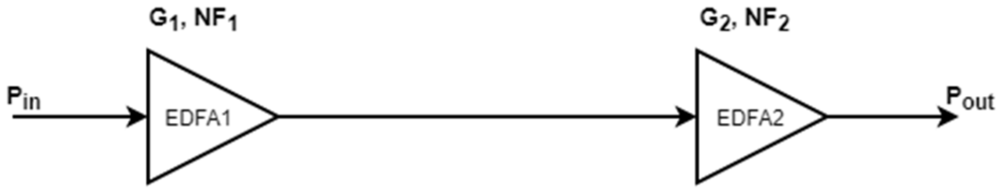
A. MOTIVATION

EDFA can be typically used as a power amplifier (or booster), an optical pre-amplifier, or as an in-line amplifier. All of these have different requirements to satisfy and, in many cases, a single-stage EDFA (SS-EDFA) cannot meet all these requirements simultaneously. For example, when an EDFA is used as an in-line amplifier all the following conditions must be met over a wide input power dynamic range: high gain, high output power, and low noise figure (NF). It is difficult to satisfy all these three requirements with a SS-EDFA because to achieve high gain, the fiber length must be large, but this will increase the NF (which is undesirable). To achieve low NF, short EDF length is required to ensure high population inversion. A multi-stage EDFA is a viable solution to this problem, wherein the first stage is designed to be an efficient pre-amplifier with subsequent stages designed as a booster [6]. A multi-stage EDFA can be designed in various ways based on the target application or a desired criterion. The following distinct features of a multi-stage EDFA help in overcoming the limitations of a SS-EDFA: 1) the ability to alter the design of each SS-EDFA in the multi-stage configuration and 2) the ability to incorporate different optical elements in the interstage within the multistage EDFA. Both these features lead to performance enhancement of the multistage EDFA compared to a single stage EDFA. In [7], [8], a dual-stage EDFA has been formed using two differently doped fibers to achieve a flat-gain wide band EDFA. In [7], a triple pass hybrid EDFA was presented, with a hafnium-bismuth erbium doped fiber (HB-EDF) and a bismuth erbium doped fiber (Bi-EDF) as the gain medium in the first and second stage respectively and employing two circulators to support the triple pass of the optical signal. The coupling ratios and the length of EDFs for dual-stage L-band EDFA were investigated in [9] by controlling the pump power distribution between the two stages. Here a flat gain of 17 dB and NF < 6.7 dB was achieved over the L-band region. Using a novel dual-stage quadruple pass (DSQP) method, an EDFA with a maximum gain of 62.56 dB and 3.98 dB NF was demonstrated in [10] and this DSQP EDFA included two tunable band pass filters (TBF) between the ports of the interstage circulator. These TBF were the key to achieving the high gain in DSQP EDFA as they filtered out the ASE noise. In [11], a wide-band dual-stage dual pass Bi-EDFA for C- and L- band was demonstrated. Here, both the stages were of Bi-EDF, but of different length and a broadband fiber Bragg grating (FBG) was used as interstage element to avoid the gain saturation in C-band. A dual-stage S-band EDFA was demonstrated in [12]. Here a broadband FBG or a wavelength division multiplexing (WDM) coupler was incorporated in the interstage for filtering the unwanted forward C-band ASE power and a gain improvement of 4 to 9.2 dB in 1480-1512nm range was achieved with minimal NF penalty. When a gain-flattening filter is used in the interstage between two EDFAs in a DS-EDFA configuration, it aids in providing automated signal-power control [13]. A theoretical investigation with simulated results for the three-stage and four-stage L-band EDFA with 12 dB interstage loss has been shown in [14]. The use of an interstage narrow bandpass optical filter has been proven to enhance the gain and output power of a DS-EDFA [6], [15]–[19]. The use of an interstage optical bandpass filter (OBPF) of 3 nm bandwidth has been shown to improve the signal gain by 9.72 dB and output signal power by 9.75dB for an input signal of −50dBm [18]. An optical limiting amplifier (OLA) based on DS-EDFA using a synchronized etalon filter for WDM application was reported to provide higher gain, lower noise figure and wider dynamic range than an OLA based on simple DS-EDFA with just an interstage isolator [20]. A hybrid optical amplifier to provide amplification over C- and L-band was experimentally demonstrated using three stages: the 1^{st} stage consisting of an EDFA pumped at 980 nm, the 2^{nd} stage with SOA and the 3^{rd} stage with an EDFA pumped at 1480 nm, with total EDF length reduced compared to the conventional L-band EDFA [21]. All the works discussed so far have a complex design and/or stringent design requirements. The primary motivation for the work presented in this paper is the desire to achieve a high gain EDFA contributing low ASE noise suitable for long distance transmission. It is also desirable to have a multi-stage EDFA design that is less complex and easier to implement using readily available SS-EDFAs.

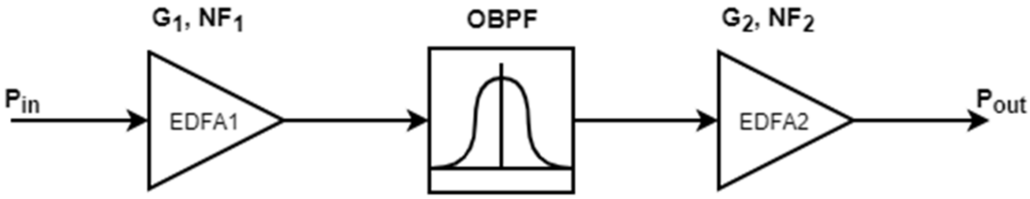
B. CONTRIBUTION

Although many of the articles discussed in the previous paragraph examine the device-level performance and characteristics of a multi-stage EDFA or DS-EDFA, there is a lack of a system-level investigation on the impact of using DS-EDFA on the system performance. The work in this paper will address this issue. The approach of utilizing two identical EDFAs in back-to-back configuration or with an interstage OBPF has not been investigated so far to our knowledge. This paper seeks to address these issues by analyzing the impact of DS-EDFA (formed using identical SS-EDFAs) on the system's optical signal to noise ratio (OSNR) and bit-error-rate (BER) performance. The advantage of using identical EDFAs in a DS-EDFA lies in their easier practical implementation and cost-effectiveness (due to ability to use readily available EDFAs) compared to a DS-EDFA that requires non-identical EDFAs in each of its stages. In addition, the impact of the placement of this DS-EDFA in the FOC system is also analyzed and it will be shown how the placement of the proposed DS-EDFA at the start of the amplifier cascade will serve as the optimum position in a long haul FOC system.

In the work presented, the simulation tool – OptSim (by Synopsys) is employed. Though, in this work only EDFAs are employed in the dual-stage configuration (for the reasons mentioned earlier in this section), it is noteworthy to mention that work such as [22] have previously demonstrated a cascade of two identical SOAs for the formation of a dual-stage



(a)



(b)

FIGURE 1. A simple functional block diagram for a dual stage EDFA (DS-EDFA) (a) without and (b) with an interstage optical bandpass filter (OBPF).

optical amplifier, which extend the reach in upstream direction of a 10 Gb/s time-division multiplexed passive optical network (TDM -PON).

In the next section, the model for a dual-stage EDFA (DS-EDFA) consisting of identical SS-EDFAs is described along with a comparison for DS-EDFA's gain profile obtained using OptSim model and a numerical model in MATLAB. Section III describes the model for an FOC system incorporating a single DS-EDFA in the cascade of EDFAs. The results obtained from the OptSim model and the numerical analysis are discussed in Section IV. Finally, key conclusions from the work are summarized in Section V.

II. DS-EDFA GAIN

This paper concentrates on the DS-EDFA formed using two identical SS-EDFAs with the first EDFA (EDFA1) compensating for the fiber attenuation and the second EDFA (EDFA2) providing some additional gain required to enhance the signal strength. Fig. 1(a) shows a very simple functional block diagram of a DS-EDFA formed using two identical SS-EDFAs connected back-to-back and Fig. 1 (b) shows the same with the inclusion of an interstage optical bandpass filter (OBPF). The insertion loss incurred by the various devices in the path of the optical signal (from input to output port of DS-EDFA) is assumed to be negligible. The signal gain of the SS-EDFA used in DS-EDFA is given as [1], [23],

$$G = G_0 \exp\left(\frac{-(G-1)}{P_s} P_{in}\right) = 1 + \frac{P_s}{P_i} \ln\left(\frac{G_0}{G}\right) \quad (1)$$

where G_0 is unsaturated gain of the EDFA, P_{in} is the input signal power and P_{s} is the amplifier saturation power, defined as the internal power level at which the gain per unit length has been halved [24]. The output signal power is given as [1],

$$P_{\text{out}}(P_{\text{in}}) = G(P_{\text{in}})\, P_{\text{in}} \quad (2)$$

For small input signal powers, the gain variation is small, but as with any amplifier, as the output power increases, EDFA's gain starts to saturate. The output saturation power, P_{outsat} is defined to be the output power at which EDFA gain is reduced by 3 dB from its maximum unsaturated gain, G_0. The saturated gain, $G_{\text{sat}}(\text{dB}) = \text{G (dB)} - 3$ dB. The relationship between output saturation power (P_{outsat}) and saturation power (P_{s}) is represented as [1],

$$P_{\text{outsat}} = \frac{G_0 \ln 2}{G_0 - 2} P_{\text{s}} \approx P_{\text{s}} \ln 2 \quad (3)$$

Equations (1)-(3) are used to numerically model the two identical EDFAs used in DS-EDFA as shown in Fig. 1. As the input power to EDFA1 is low (due to fiber attenuation), the EDFA1 remains in the unsaturated regime, but the second EDFA gets driven into saturation as the output power of EDFA1 consists of amplified input signal plus the ASE noise added by itself.

For a small input signal, the ASE noise power dominates the output power of EDFA1, leading EDFA2 to saturate, i.e. $P_{inEDFA2} = P_{sig-out-EDFA1} + P_{self-ASE-EDFA1}$, $P_{self-ASE-EDFA1} \gg P_{sig-out-EDFA1}$, $P_{inEDFA2} \approx P_{self-ASE-EDFA1}$; $P_{self-ASE} = m_t N_0 B_{OPT}$ is the self-ASE noise power at the output of a single stage EDFA measured over system's optical bandwidth B_{OPT}, m_t corresponds to number of polarization modes (1 or 2), $N_0 = (1/2)\,(\text{NF}G - 1)\, h\nu$ is the ASE noise single-sided power spectral density (PSD) and NF is the noise figure of the SS-EDFA [23]. Thus, it is necessary to evaluate the effective signal gain, $G_{eff} = G_1 G_2$ contributed by DS-EDFA, where G_1 is the gain of EDFA1 and G_2 is the gain of EDFA2.

To understand how accurately OptSim models DS-EDFA, it is compared with a numerically modelled (in MATLAB) DS-EDFA. The parameters used for both models are shown in Table 1 (as described in [23]). Fig.2 compares the gain (dB)

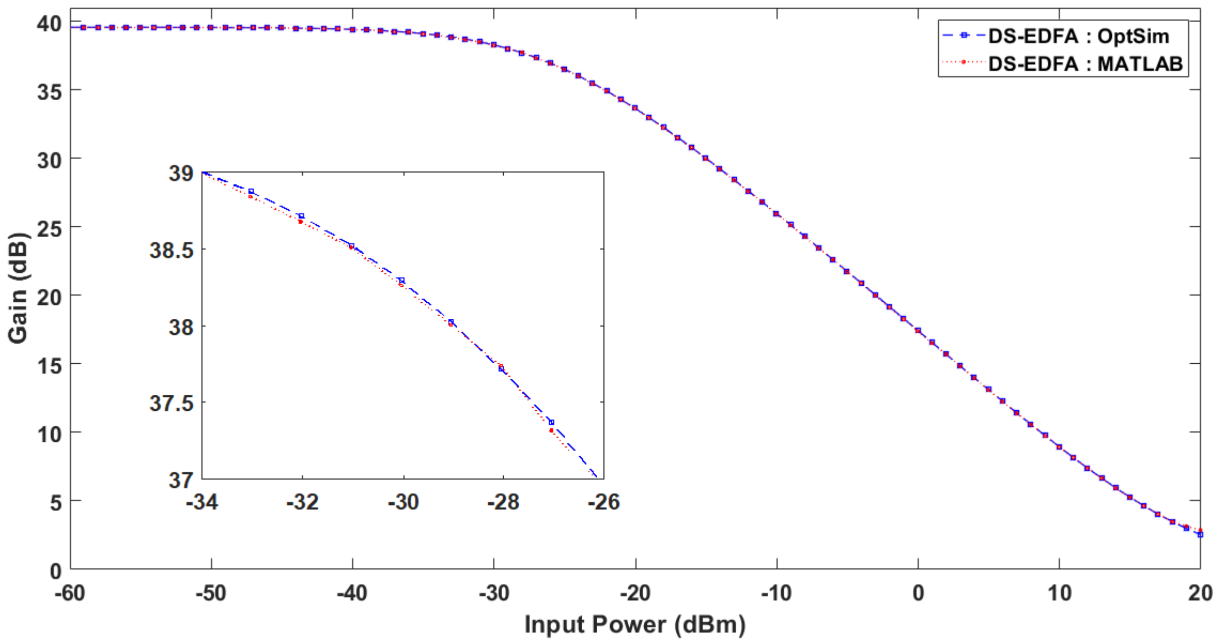


FIGURE 2. Gain (dB) vs input power (dBm) comparison for DS-EDFA (without interstage filter) obtained from simulation model in OptSim and numerical model in MATLAB.

TABLE 1. Single – stage EDFA parameters [23].

Symbol	Parameter	Value	Unit
G_0	Unsaturated Gain	25	dB
P_{outsat}	Output Saturation Power	7	dBm
λ	Operating Wavelength	1550	nm
NF	Noise Figure	6	dB

vs input power (dBm) characteristic of DS-EDFA (without an interstage OBPF) modelled using OptSim (see the blue curve with square markers) with the same modelled in MATLAB using equations (1)-(3) (refer to the red curve with circular markers). Fig. 2 clearly demonstrates that OptSim modelled the DS-EDFA accurately. Intuitively, overall effective gain is expected to be around 50 dB for small input signals, but due to presence of high ASE noise at the input of EDFA2, the gain offered by EDFA2 is lower, 39.56 dB. ASE noise power from EDFA1 drives EDFA2 into saturation, lowering its gain as observed in the overall gain profile of DS-EDFA.

To achieve higher effective gain, an interstage optical band-pass filter (OBPF) is used in the DS-EDFA design. To observe the impact of using an interstage OBPF, OBPFs with different bandwidths were used. Fig. 3 shows the gain vs input power characteristic for the system when no interstage OBPF is used as well as when an interstage raised cosine type OBPF of 3 nm, 9 nm or 15 nm bandwidth is used. It can be observed that using a smaller OBPF bandwidth, B_{OF} of 3 nm is more effective in reducing ASE noise and increasing the EDFA2 gain, which increases the overall effective gain of the DS-EDFA. Note that bandwidths smaller than 3 nm can be used based on the system under consideration. Fig. 4 provides gain (dB) vs input power (dBm) comparison between no interstage OBPF and with different types of interstage OBPF of 3 nm bandwidth. Raised cosine OBPF exhibits better performance compared to the Super Gaussian and Bessel type OBPF of same bandwidth. It can be observed from Fig. 3 and 4 that DS-EDFA with different interstage OBPFs yield the same gain at high input signal powers. This is to be expected, because for high input signal powers, as the N_0 is very low, the OBPF's bandwidth as well the transmission profile has no significant impact on the EDFA gain.

III. FOC SYSTEM MODEL WITH DS-EDFA IN THE CASCADE OF EDFAS

Fig. 5 shows a single wavelength FOC system model with a cascade of n EDFAs. This system consists of a continuous-wave laser transmitter, an optical receiver, optical fibers, and several EDFAs. Here, the cascade of EDFAs consist of several SS-EDFAs but only one DS-EDFA (formed using identical SS-EDFAs as described in the previous section). The Fig. 5 shows that the DS-EDFA can be placed at the start of the cascade (Position 1), in the middle of the cascade (Position 2) or at the end of the cascade (Position 3) in this system. For simplicity, a homogenous system is considered by keeping all inter-amplifier fiber sections identical. In addition, the other EDFAs used in the cascade are identical to the SS-EDFA used in DS-EDFA. The DS-EDFA may or may not include an interstage OBPF as shown in the fig. 5.

A. SINGLE WAVELENGTH FOC SYSTEM WITH DS-EDFA IN THE EDFA CASCADE

In a FOC system where a cascade of EDFAs is used, the accumulated ASE noise dominates the BER performance of

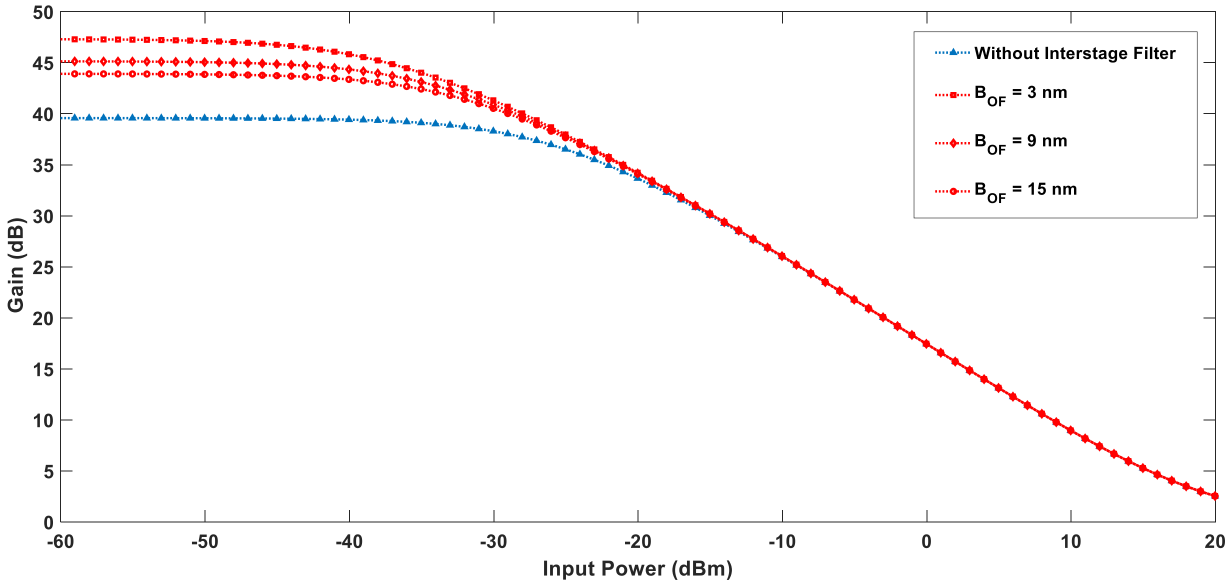


FIGURE 3. Gain improvement of DS-EDFA with inclusion of an interstage Raised Cosine type OBPF of 3 nm, 9 nm and 15 nm bandwidth (B_{OF}) respectively.

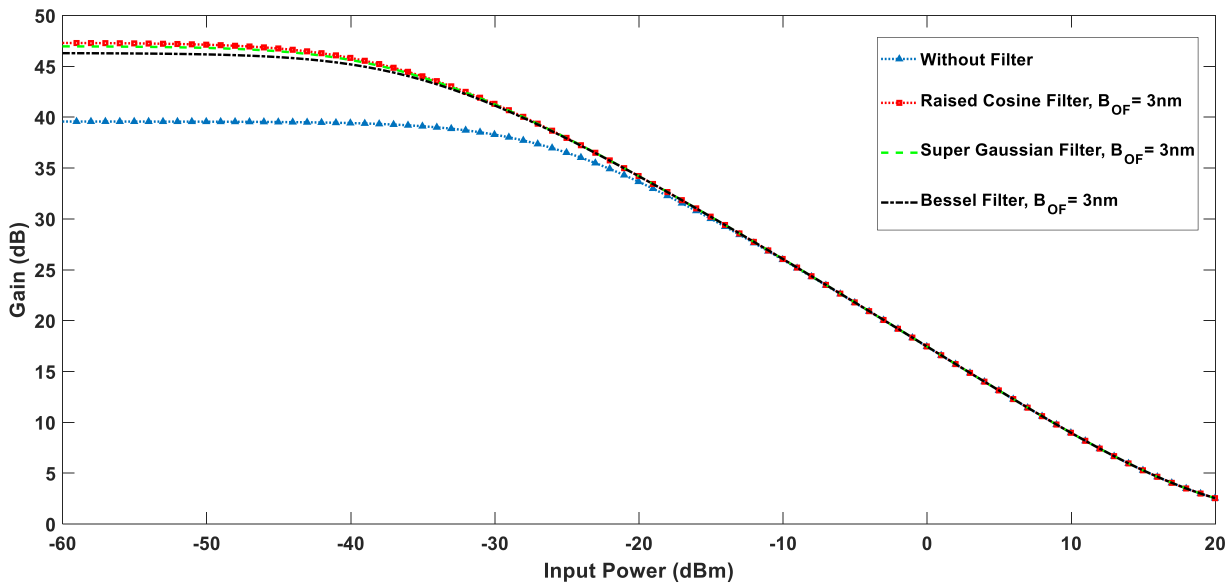


FIGURE 4. Gain improvement of DS-EDFA in presence of different types of interstage OBPF of 3 nm bandwidth (B_{OF}).

the system. To determine how DS-EDFA helps in reducing the ASE noise accumulation, it is therefore necessary to determine the optical signal power and ASE noise power at the output of each EDFA in the system. Firstly, consider a case where each of the n EDFAs in the cascade are SS-EDFAs. Here, the total power at the input of the i^{th} EDFA, P_{in_i} is,

$$P_{in_i} = P_{out_{i-1}}/L_i = P_{SIG-in_i} + P_{ASE-in_i} \quad (i = 2, \ldots, n) \tag{4}$$

where $P_{out_{i-1}}$ is the total power at the output of the previous EDFA in the cascade and L_i is the total loss (due to fiber attenuation) in each inter-amplifier section (throughout the analysis presented in this paper, it is assumed that the insertion losses incurred due to the various components are negligible compared to fiber attenuation and hence are neglected). P_{SIG-in_i} is the signal power and P_{ASE-in_i} is the total ASE noise power at the input of i^{th} EDFA measured over system's optical bandwidth B_{OPT}. For the first EDFA ($i = 1$), there is no ASE noise present, i.e., $P_{ASE-in_1} = 0$ (transmitter source ASE noise is assumed to be negligible), the total power at its input is,

$$P_{in_1} = P_{SIG-in_1} = P_{TX}/L_1 \tag{5}$$

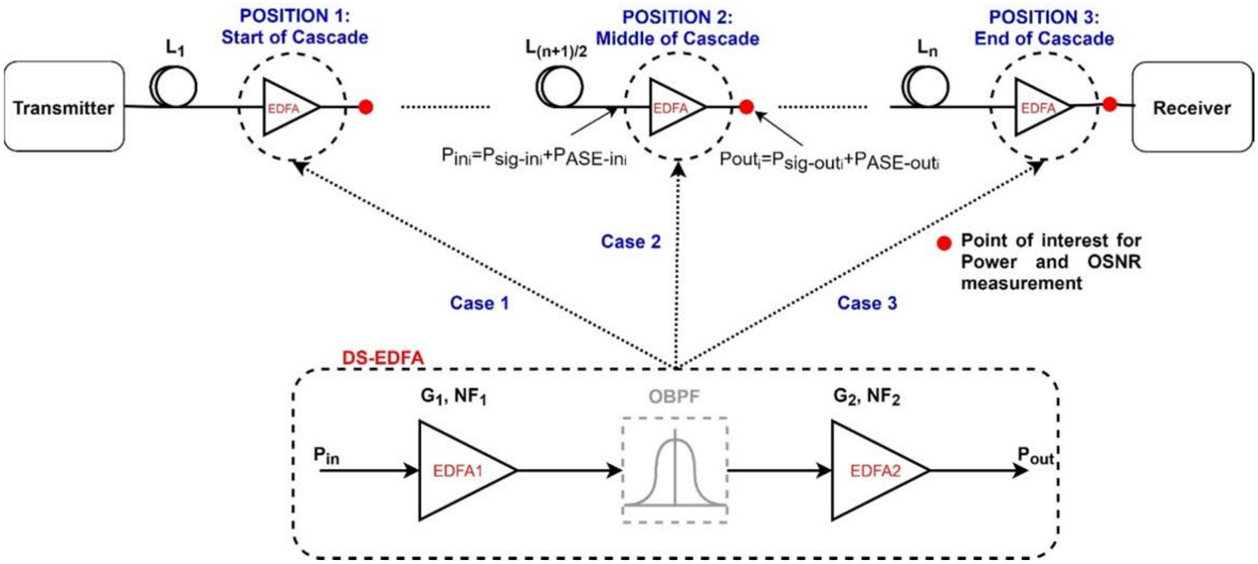


FIGURE 5. Cascade of EDFAs in the FOC system under consideration. Here in case 1 a DS-EDFA replaces a SS-EDFA at the start of the cascade (Position 1), in case 2 a DS-EDFA replaces a SS-EDFA at the middle of the cascade (Position 2) and in case 3 a DS-EDFA replaces a SS-EDFA at the end of the cascade (Position 3). DS-EDFA may or may not include an interstage optical bandpass filter (OBPF).

where P_{TX} is the total transmitted power and L_1 is the total loss (due to fiber attenuation) in between transmitter and the first EDFA.

The total power at the output of the i^{th} EDFA is given as,

$$\begin{aligned} P_{out_i} &= P_{in_i} G_i\left(P_{in_i}\right) + P_{self-ASE_i}\ (i = 1, \ldots, n) \\ &= \left(P_{SIG-in_i} + P_{ASE-in_i}\right) G_i\left(P_{in_i}\right) + P_{self-ASE_i} \\ &= \underbrace{P_{SIG-in_i} G_i\left(P_{in_i}\right)} + \underbrace{P_{ASE-in_i} G_i\left(P_{in_i}\right) + P_{self-ASE_i}} \\ &= P_{SIG-out_i} + P_{ASE-out_i} \end{aligned} \tag{6}$$

where G_i is the i^{th} EDFA gain which is dependent on the instantaneous optical signal power at the input of the i^{th} EDFA, $P_{self-ASE_i} = m_t N_{0_i} B_{OPT}$, $N_{0_i} = (1/2)\left(\mathrm{NF}_i G_i - 1\right) h\nu$ is the ASE noise single-sided power spectral density (PSD) and NF_i is the noise figure of the i^{th} EDFA. $P_{SIG-out_i}$ is the signal power and $P_{ASE-out_i}$ is the total ASE noise power (measured over system's optical bandwidth B_{OPT}) at the output of the i^{th} EDFA. It is important to note that there is a difference between the ASE noise power measured within a specific optical channel bandwidth, like in case for OSNR measurement and the total ASE noise power which is defined over the full spectral range of the EDF emission (which is defined in this work as system bandwidth, B_{OPT}). The ASE noise generated by an EDFA depends on its gain, signal wavelength and other design characteristics which varies from one EDFA to another [13], [25].

From (6), equation (4) can be rewritten as,

$$\begin{aligned} P_{in_i} &= P_{out_{i-1}}/L_i = \left(P_{SIG-out_{i-1}} + P_{ASE-out_{i-1}}\right)/L_i \\ &\quad \times (i = 2, \ldots, n) \end{aligned} \tag{7}$$

B. FOR DS-EDFA INCORPORATED IN THE CASCADE

In the FOC system under consideration, only one DS- EDFA can be incorporated in the system and can be placed at the start of the cascade (Position 1), in the middle of the cascade (Position 2) or at the end of the cascade (Position 3), as shown in fig. 5. The total power at the input of EDFA1 (see fig1 (a)) is, $P_{in-EDFA1} = P_{in_i}$ and the total power at the output of EDFA1 is,

$$\begin{aligned} P_{out-EDFA1} &= P_{in-EDFA1} G_{EDFA1}\left(P_{in-EDFA1}\right) \\ &\quad + P_{self-ASE-EDFA1} \\ &= P_{SIG-out-EDFA1} + P_{ASE-out-EDFA1} \end{aligned} \tag{8}$$

where $P_{self-ASE-EDFA1}$ is the self-ASE noise power (measured over system's optical bandwidth B_{OPT}) at the output of EDFA1 and $P_{ASE-out-EDFA1}$ is the total ASE noise power (measured over system's optical bandwidth B_{OPT}) at the output of EDFA1.

The power at the input of EDFA2 is,

$$\begin{aligned} P_{in-EDFA2} &= P_{out-EDFA1} \\ &= P_{SIG-out-EDFA1} + P_{ASE-out-EDFA1} \end{aligned} \tag{9a}$$

However, if an OBPF is present at the interstage, then

$$\begin{aligned} P_{in-EDFA2} &= P_{SIG-out-EDFA1} \\ &\quad + \left(P_{ASE-out-EDFA1}/\alpha(\lambda)_{OF}\right) \end{aligned} \tag{9b}$$

where $\alpha(\lambda)_{OF}$ is the wavelength-dependent attenuation offered by the interstage OBPF of bandwidth B_{OF}, $B_{OF} \ll B_{OPT}$. The exact value of this attenuation depends on the transfer function of the type of OBPF used.

TABLE 2. System parameters.

Symbol	Parameter	Value	Unit	Reference
P_{avTX}	Transmitted Power	-30 to -5	dBm	[23]
R_B	Bit Rate	10	Gbps	[23]
λ	Operating Wavelength	1550	nm	[23]
α	Fiber Attenuation	0.2	dB/km	[23]
A_{eff}	Effective Area	80	μm^2	[23]
PMD	Polarization Mode Dispersion	≤ 0.1	ps/$\sqrt{}$km	[23]
l	Length of each fiber section	125	km	[23]
B_{OF}	Interstage Raised Cosine type OBPF Bandwidth	3	nm	[6], [18]
B_{OPT}	System Bandwidth	62.5	nm	[1], [23], [24], [29]
B_E	Electrical Bandwidth	5	GHz	[23]
B_{OSNR}	Resolution Bandwidth for OSNR measurement	10	GHz	[24], [29], [34]

TABLE 3. Comparison between OptSim and MATLAB values for the total power obtained at the output of different EDFAs in the system incorporating a cascade of 3 EDFAs (without DS-EDFA).

Input Power (dBm)	Total Output Power (dBm)						
	OptSim			MATLAB			
	EDFA at i=1	EDFA at i=2	EDFA at i=3	EDFA at i=1	EDFA at i=2	EDFA at i=3	Without DS-EDFA
-30	-2.011	0.631	1.914	-2.013	0.636	1.912	
-5	-0.447	1.356	2.298	-0.431	1.360	2.289	

TABLE 4. Comparison between OptSim and MATLAB values for the total power obtained at the output of different EDFAs in the system incorporating a cascade of 3 EDFAs, with DS-EDFA(without interstage OBPF) at position 1.

Input Power (dBm)	Total Output Power (dBm)								
	OptSim				MATLAB				
	DS-EDFA at i=1 (o/p of EDFA1)	DS-EDFA at i=1 (o/p of EDFA2)	EDFA at i=2	EDFA at i=3	DS-EDFA at i=1 (o/p of EDFA1)	DS-EDFA at i=1 (o/p of EDFA2)	EDFA at i=2	EDFA at i=3	DS-EDFA at the start of cascade
-30	-2.011	12.573	8.578	6.492	-2.013	12.554	8.532	6.463	
-5	-0.447	13.042	8.796	6.607	-0.431	13.017	8.792	6.600	

TABLE 5. Comparison between OptSim and MATLAB values for the total power obtained at the output of different EDFAs in the system incorporating a cascade of 3 EDFAs, with DS-EDFA (without interstage OBPF) at position 2.

Input Power (dBm)	Total Output Power (dBm)								
	OptSim				MATLAB				
	EDFA at i=1	DS-EDFA at i=2 (o/p of EDFA1)	DS-EDFA at i=2 (o/p of EDFA2)	EDFA at i=3	EDFA at i=1	DS-EDFA at i=2 (o/p of EDFA2)	DS-EDFA at i=2 (o/p of EDFA2)	EDFA at i=3	DS-EDFA at the middle of cascade
-30	-2.011	0.631	13.361	8.948	-2.013	0.636	13.377	8.931	
-5	-0.447	1.356	13.567	9.040	-0.431	1.360	13.530	9.028	

The power at the output of EDFA2 is,

$$
\begin{aligned}
P_{out-EDFA2} &= P_{in-EDFA2}G_{EDFA2}\left(P_{in-EDFA2}\right) \\
&\quad + P_{self-ASE-EDFA2} \\
&= P_{SIG-out-EDFA2} + P_{ASE-out-EDFA2}
\end{aligned} \tag{10}
$$

C. OSNR AND BER ANALYSIS

Optical signal-to noise ratio (OSNR) is an important parameter used for optical performance monitoring (OPM) of an optical network. OSNR at the output of the i^{th} EDFA is given as [23],

$$
OSNR_i\,[dB] = 10\log\left(\frac{P_{SIG-out_i}}{P_{ASE-out_i}}\right) \tag{11}
$$

where $P_{ASE-out_i}$ is the total ASE noise power at the output of i^{th} EDFA measured over the resolution bandwidth of the optical spectrum analyzer [26], $B_{OSNR} = 10$ GHz or 0.08 nm. It should be noted that OptSim uses the optical

TABLE 6. Comparison between OptSim and MATLAB values for the total power obtained at the output of different EDFAs in the system incorporating a cascade of 3 EDFAs, with DS-EDFA (without interstage OBPF) at position 3.

Input Power (dBm)	Total Output Power (dBm)								
	OptSim				MATLAB				
	EDFA at i=1	EDFA at i=2	DS-EDFA at i=3 (o/p of EDFA1)	DS-EDFA at i=3 (o/p of EDFA2)	EDFA at i=1	EDFA at i=2	DS-EDFA at i=3 (o/p of EDFA1)	DS-EDFA at i=3 (o/p of EDFA2)	DS-EDFA at the end of cascade
-30	-2.011	0.631	1.914	13.724	-2.013	0.636	1.912	13.727	
-5	-0.447	1.356	2.298	13.826	-0.431	1.360	2.289	13.817	

TABLE 7. OptSim values for the total power obtained at the output of different EDFAs in the system incorporating a cascade of 3 EDFAs, with DS-EDFA(with interstage OBPF) at position 1.

Input Power (dBm)	Total Output Power (dBm)					
	DS-EDFA at i=1 (o/p of EDFA1)	At the o/p of interstage OBPF	DS-EDFA at i=1 (o/p of EDFA2)	EDFA at i=2	EDFA at i=3	DS-EDFA with interstage OBPF at the start of cascade
-30	-2.011	-15.628	6.932	5.551	4.735	
-5	-0.447	-4.885	11.635	8.113	6.228	

TABLE 8. OptSim values for the total power obtained at the output of different EDFAs in the system incorporating a cascade of 3 EDFAs, with DS-EDFA (with interstage OBPF) at position 2.

Input Power (dBm)	Total Output Power (dBm)					
	EDFA at i=1	DS-EDFA at i=2 (o/p of EDFA1)	At the o/p of interstage OBPF	DS-EDFA at i=2 (o/p of EDFA2	EDFA at i=3	DS-EDFA with interstage OBPF at the middle of cascade
-30	-2.011	0.631	-13.047	8.276	6.323	
-5	-0.447	1.356	-5.010	11.606	8.105	

TABLE 9. OptSim values for the total power obtained at the output of different EDFAs in the system incorporating a cascade of 3 EDFAs, with DS-EDFA (with interstage OBPF) at position 3.

Input Power (dBm)	Total Output Power (dBm)					
	EDFA at i=1	EDFA at i=2	DS-EDFA at i=3 (o/p of EDFA1)	At the o/p of interstage OBPF	DS-EDFA at i=3 (o/p of EDFA2	DS-EDFA with interstage OBPF at the end of cascade
-30	-2.011	0.631	1.914	-11.781	8.892	
-5	-0.447	1.356	2.298	-5.388	11.455	

power spectrum generated in the simulation platform to evaluate the OSNR based on the signal power level and ASE noise power level obtained using the linear interpolation method to measure the noise level within the signal bandwidth [27], [28]. In the MATLAB numerical model, the ASE noise PSD is assumed to be flat within the optical bandwidth of the measurement and this results in an overestimation of the ASE noise power. Given this, the results presented in the section IV employ the optical power spectrum obtained in OptSim for the OSNR evaluation.

To analyze and better understand the impact of the OSNR on the system performance, it is valuable to examine the bit error rate (BER) for the system. BER is often defined through Q-factor, which is conceptually close to OSNR [29]. Thus, it is useful to use the relationship between Q-factor and OSNR. As optical amplification results in ASE noise, which dominates the receiver thermal and shot noise [30], the Q-factor can be evaluated by neglecting the thermal and shot noise. The Q-factor is given by [23]–[25], [29], [31],

$$Q_i = \frac{2\sqrt{\frac{B_{OSNR}}{B_E}\mathrm{OSNR}_i}}{1+\sqrt{1+4\mathrm{OSNR}_i}} \tag{12}$$

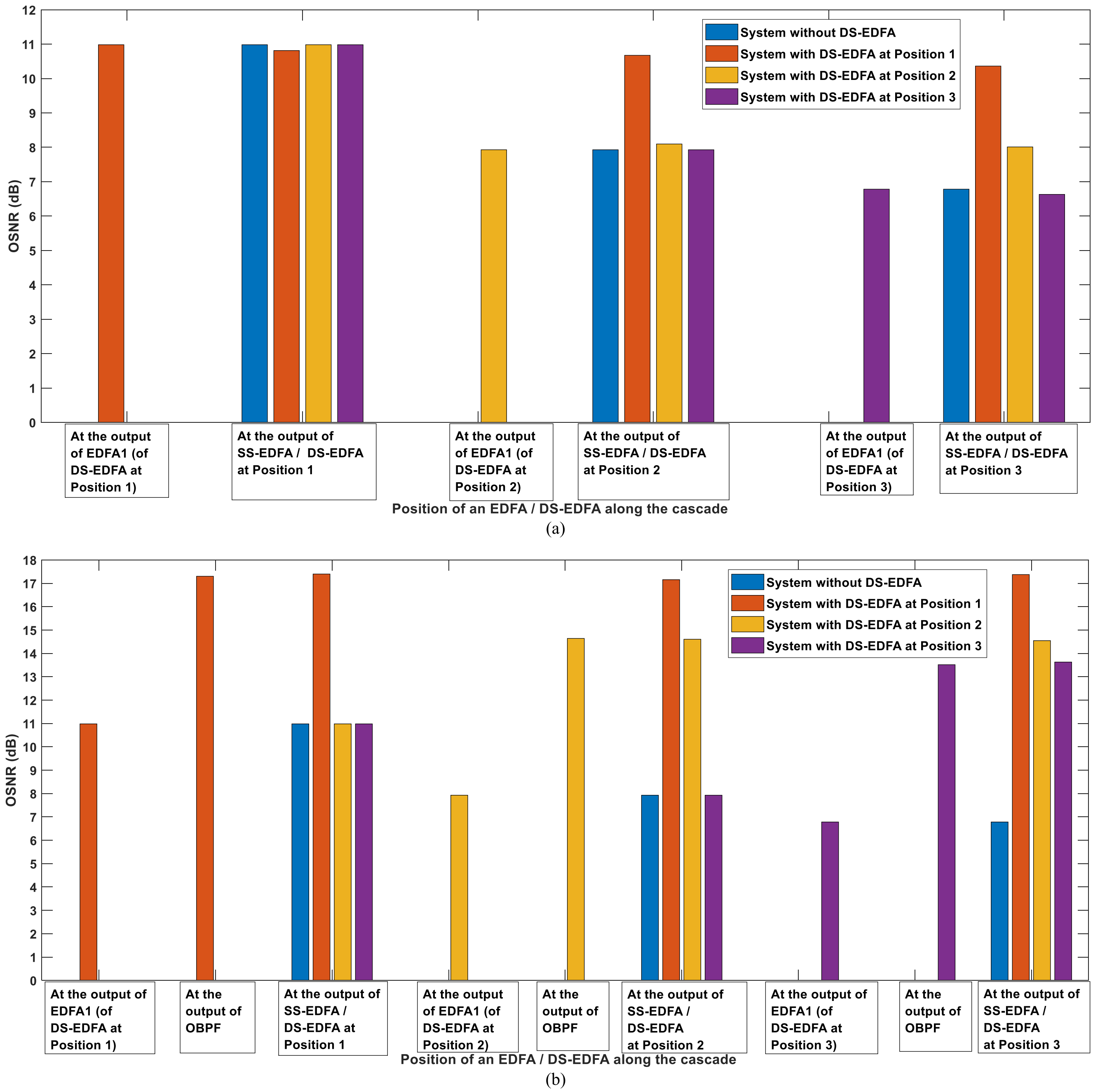


FIGURE 6. OSNR at the output of different SS-EDFAs and DS-EDFA in the cascade (a) without interstage OBPF and (b) with interstage OBPF, for $P_{avTX} = -20$dBm.

where B_E is the bandwidth of the optical receiver. Eq. (12) can be used to derive the OSNR needed to obtain a given BER, for a system with only amplifier noise [25]. The BER for the system under consideration is evaluated from the Q obtained using the OSNR evaluated at the end of the cascade i.e., at the output of the last EDFA ($i = n$). The equation for BER is given by [1], [23], [24], [29], [32],

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\frac{Q_n}{\sqrt{2}}\right) \tag{13}$$

IV. RESULTS AND ANALYSIS

The signal at the transmitter output is assumed to have a non-return-to-zero on-off keying (NRZ-OOK) format. Throughout the analysis presented in this section, all the SS-EDFAs used in the cascade are assumed identical in terms of their gain profile. The DS-EDFA placed at any of the three positions (as mentioned in section III) is also made of identical SS-EDFAs, except in section IV-C and section IV-D where the impact of different output saturation powers for EDFA1 and EDFA2 of DS-EDFA and number of stages in

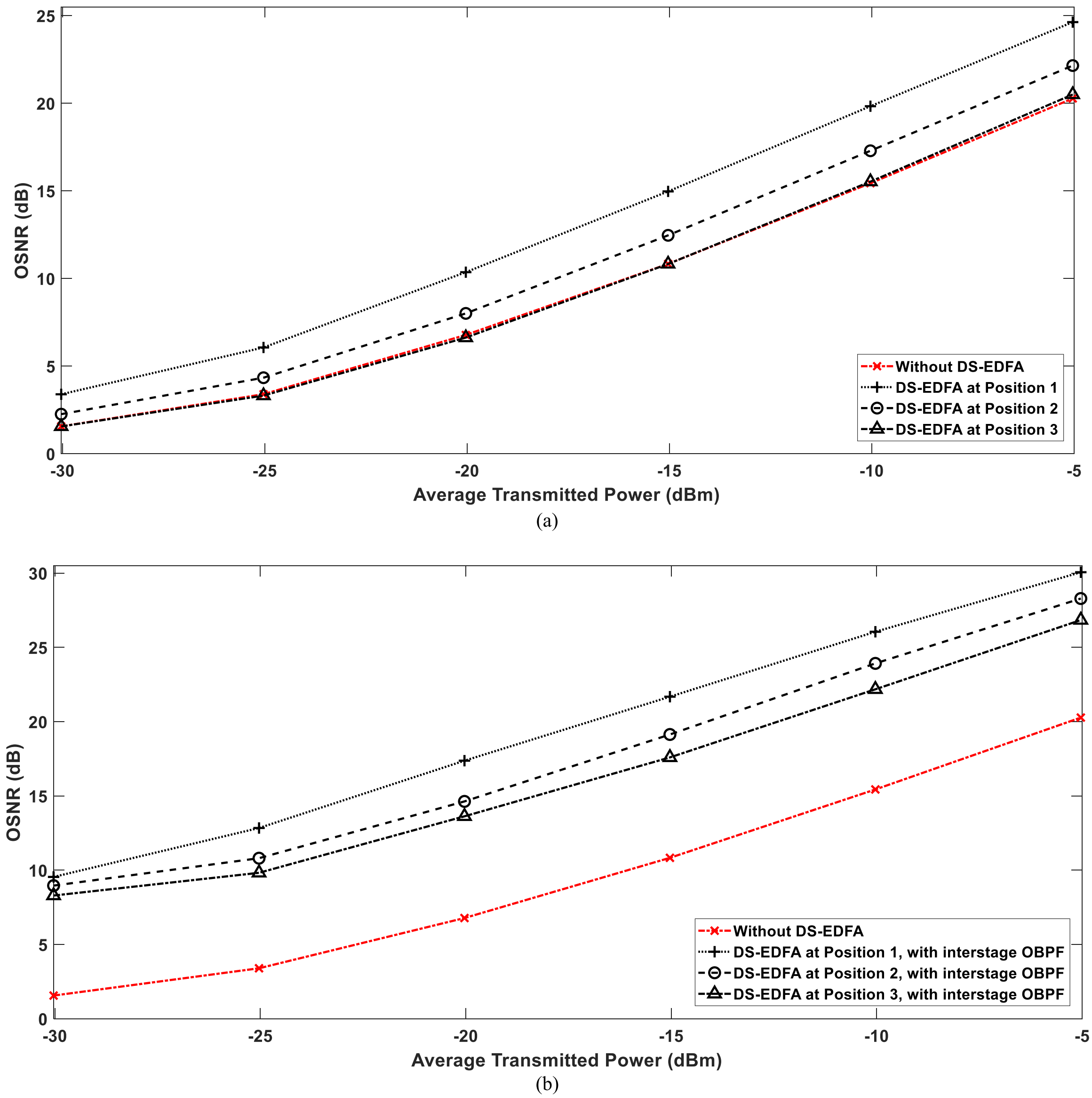


FIGURE 7. OSNR at the end of the cascade v/s Average Transmitted Power for the system (a) without interstage OBPF (b) with interstage OBPF.

a multistage EDFA are investigated respectively. Note that a raised cosine type OBPF of 3 nm bandwidth is used as an interstage OBPF throughout this analysis. The parameters required for the design of each homogenous inter-amplifier section of the cascade and the system parameters are shown in Table 2. The system parameter values in Table 2 are available in the literature. For a SS-EDFA, parameters are the same as provided in Table 1.

The FOC system with the cascade of 3 EDFAs as shown in Fig. 5 is modelled in OptSim as well as numerically modelled in MATLAB using the equations provided in section III (without the inclusion of an interstage OBPF) for cross verification of results. It should be noted that the cascade can only have one DS-EDFA at either Position 1, Position 2 or Position 3 as mentioned in section II. The total average power values at the output of every SS-EDFA/DS-EDFA (marked in Fig 5 by red dots at every point of measurement) obtained from OptSim and the numerical MATLAB model for transmit powers of −30 and −5 dBm (extreme ends of transmit power range) are compared. This transmit power range is chosen to ensure that there are no non-linear effects contributing towards signal deterioration. The power values for other intermediate transmit powers were also verified but not tabulated for brevity. Table 3 provides the total output power values comparison for the case when the cascade consists of only SS-EDFAs (i.e. system without a DS-EDFA), whereas Table 4, 5 and 6 provide comparison for the cases when DS-EDFA (without an interstage OBPF) is

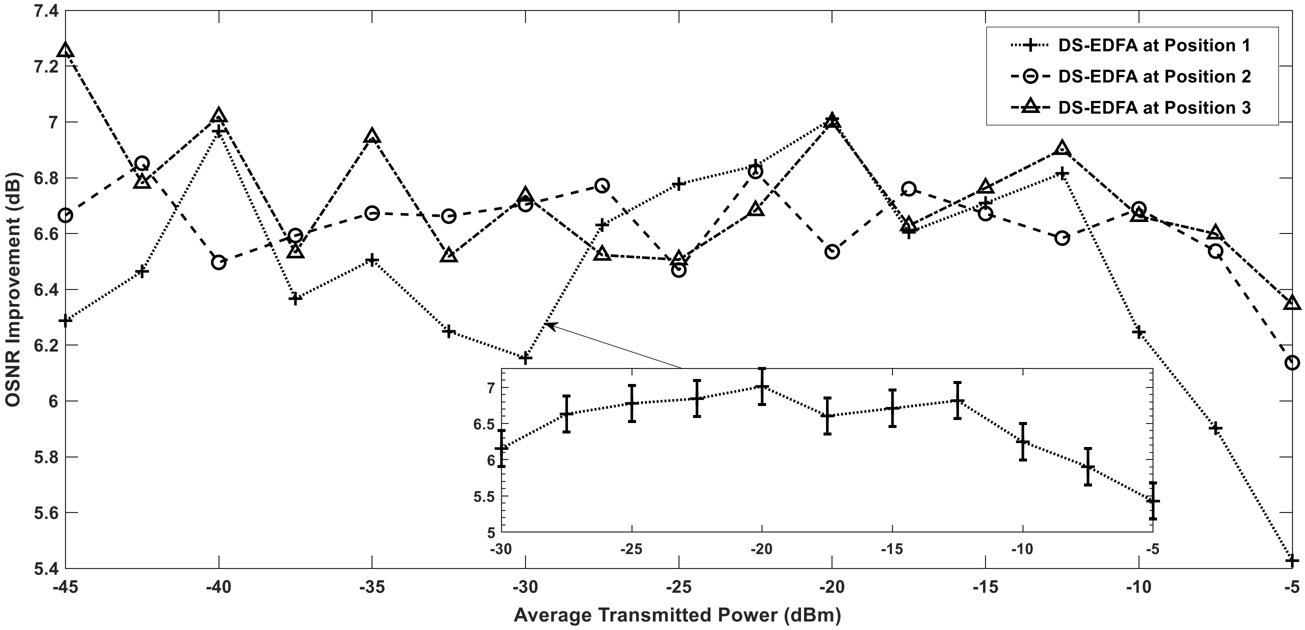


FIGURE 8. OSNR improvement achieved due to the incorporation of an interstage OBPF in DS-EDFA.

placed at position 1, position 2 and position 3 respectively in the cascade. In all the cases, the power values obtained from the OptSim model and those obtained from the numerical MATLAB model are well matched which validates OptSim's accuracy in modelling the FOC system. Given this validation, the results for the remainder of the analysis were obtained using only the OptSim model. The tables (4, 5 and 6) also show how due to the intrinsic saturation of EDFA2, the DS-EDFA provides almost constant total output power for the different transmitted powers.

Table 7, 8 and 9 present the output power values obtained in Optsim for DS-EDFA with interstage OBPF at the 3 different positions. From these tables, the impact of interstage OPBF in reducing the ASE noise accumulation is evident, while the signal power remains unchanged. In addition, these tables help to better understand the susceptibility of the system employing DS-EDFA to fiber's non-linear effects. As seen from tables 7, 8 and 9, the power at the output of DS-EDFA (with an interstage OBPF) is slightly higher than 10 dBm for $P_{avTX} = -5$ dBm, thus the transmission power can be further limited to -10 or -15 dBm, based on the application. In addition to limiting the maximum transmission power, during practical implementation, deploying a suitable power monitoring method and incorporating variable optical attenuators (VOAs) at the output of the DS-EDFA to maintain the output power within the non-linearity threshold power level (0 dBm for self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM) & stimulated Brillouin scattering (SBS) and 30 dBm for stimulated Raman scattering (SRS). As the threshold power for SRS is very high, it is not a concern in our analysis [1]. SPM is a concern for a single wavelength system as well wavelength division multiplexed (WDM) systems, whereas XPM and FWM only affect WDM systems. If the system under consideration is not using WDM e.g. TDM PONs, then SBS and SPM will be of concern. It should be noted that incorporating a VOA at the output of DS-EDFA would not change the OSNR. However, the OSNR at the successive EDFAs will be reduced by a small amount and the corresponding BER will be a little higher. Also, the combination of using DS-EDFA formed using SS-EDFAs with comparatively smaller output saturation power might be helpful. Further, due to the losses incurred by the connectors used in the practical implementation, the actual gain of the proposed DS-EDFA configuration could be expected to decrease by a few dBs below the value obtained from the simulated and numerical models.

A. IMPACT OF DS-EDFA WITH INTERSTAGE OBPF ON THE SYSTEM PERFORMANCE

In this section, with the aid of Fig. 6 through to 10, the results of two main investigations are presented: 1) determining the best position to place a DS-EDFA in the cascade of EDFAs and 2) understanding the impact of including an interstage OBPF on the system performance. OSNR and BER will serve as the metrics for these investigations. The FOC system with cascade of 3 EDFAs is considered with system parameters as mentioned in Table 2.

Fig. 6(a) shows the OSNR degradation after every successive EDFA, for transmit power, $P_{\text{avTX}} = -20$ dBm, when no interstage OBPF is employed. Without any DS-EDFA in the system, OSNR degrades from 10.98 dB at the output of SS-EDFA at position 1 to 7.93 dB at the output of SS-EDFA at position 2, which further degrades to 6.78 dB at the output of SS-EDFA at position 3. However, when

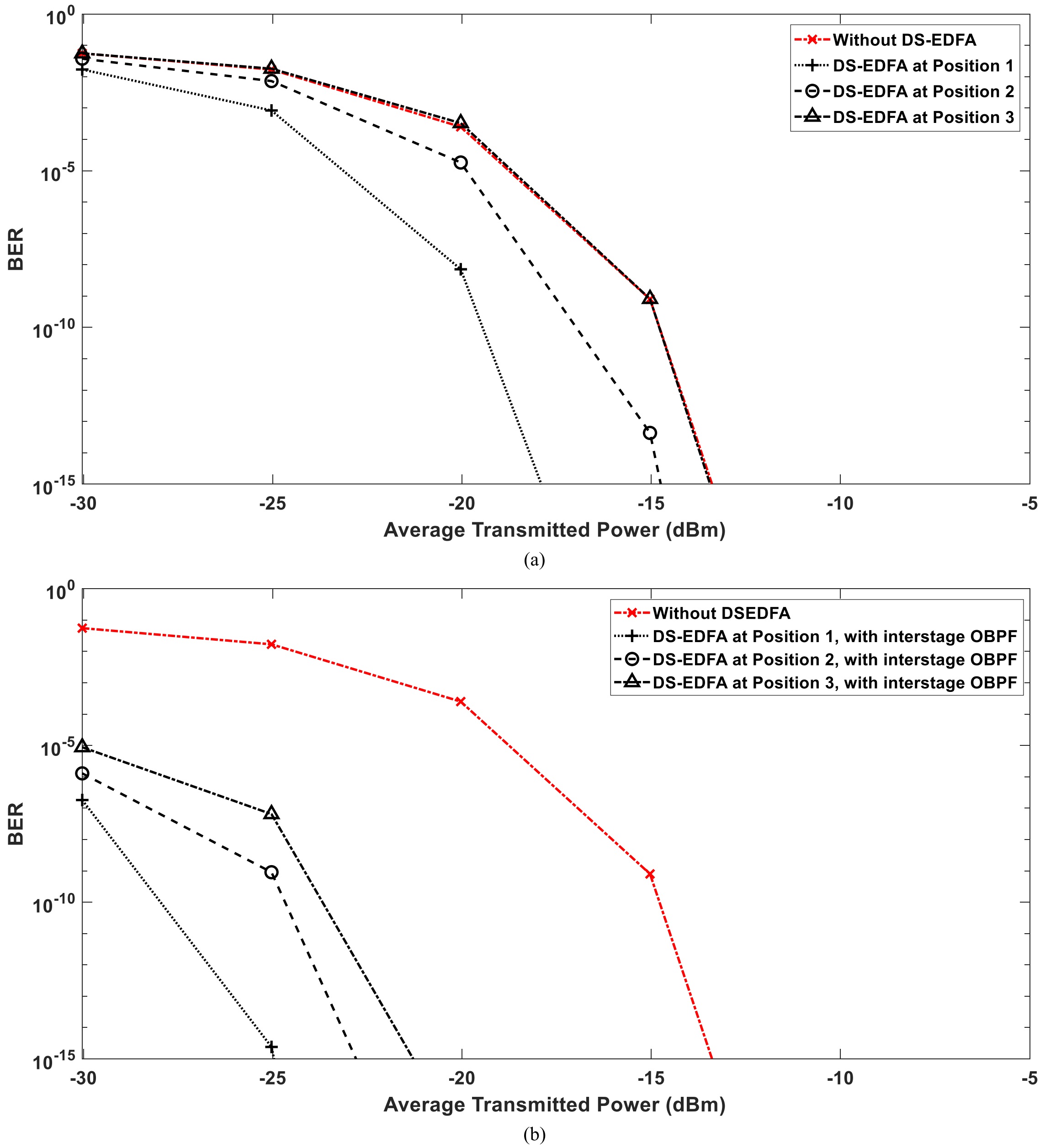


FIGURE 9. BER v/s Average Transmitted Power (a) without interstage OBPF (b) with interstage OBPF.

DS-EDFA is placed in the system at position 1 and 2, the OSNR at the output of SS-EDFA at position 3 (i.e. at the end of cascade) was 10.36 dB and 8 dB respectively. Thus, inclusion of DS-EDFA in the system proves advantageous, except when DS-EDFA is placed at position 3 where the OSNR obtained at its output was 6.6 dB. Due to the increased ASE noise accumulation brought about by using DS-EDFA at position 3, there was no improvement in the OSNR performance compared to the system without any DS-EDFA. From Fig. 6(a) it can be seen that the best placement of DS-EDFA is at position 1, as it provides better OSNR performance. As DS-EDFA at position 1 launches high power in the later part of the cascade, the successive SS-EDFAs were driven into saturation and contributed comparatively lower gain and lower ASE noise. However, there is still an increase in accumulation of ASE noise compared to the system without any DS-EDFA and as discussed in section II, the high ASE noise from EDFA1 saturates EDFA2 and DS-EDFA's effective gain was not very high. Solution for both these problems was to incorporate a narrow-band interstage OBPF in DS-EDFA which reduces the ASE noise power at the input of EDFA2, as described in section II and III. Fig 6 (b) shows the OSNR improvement at the output of the interstage OBPF, thereby demonstrating overall reduction in the OSNR degradation

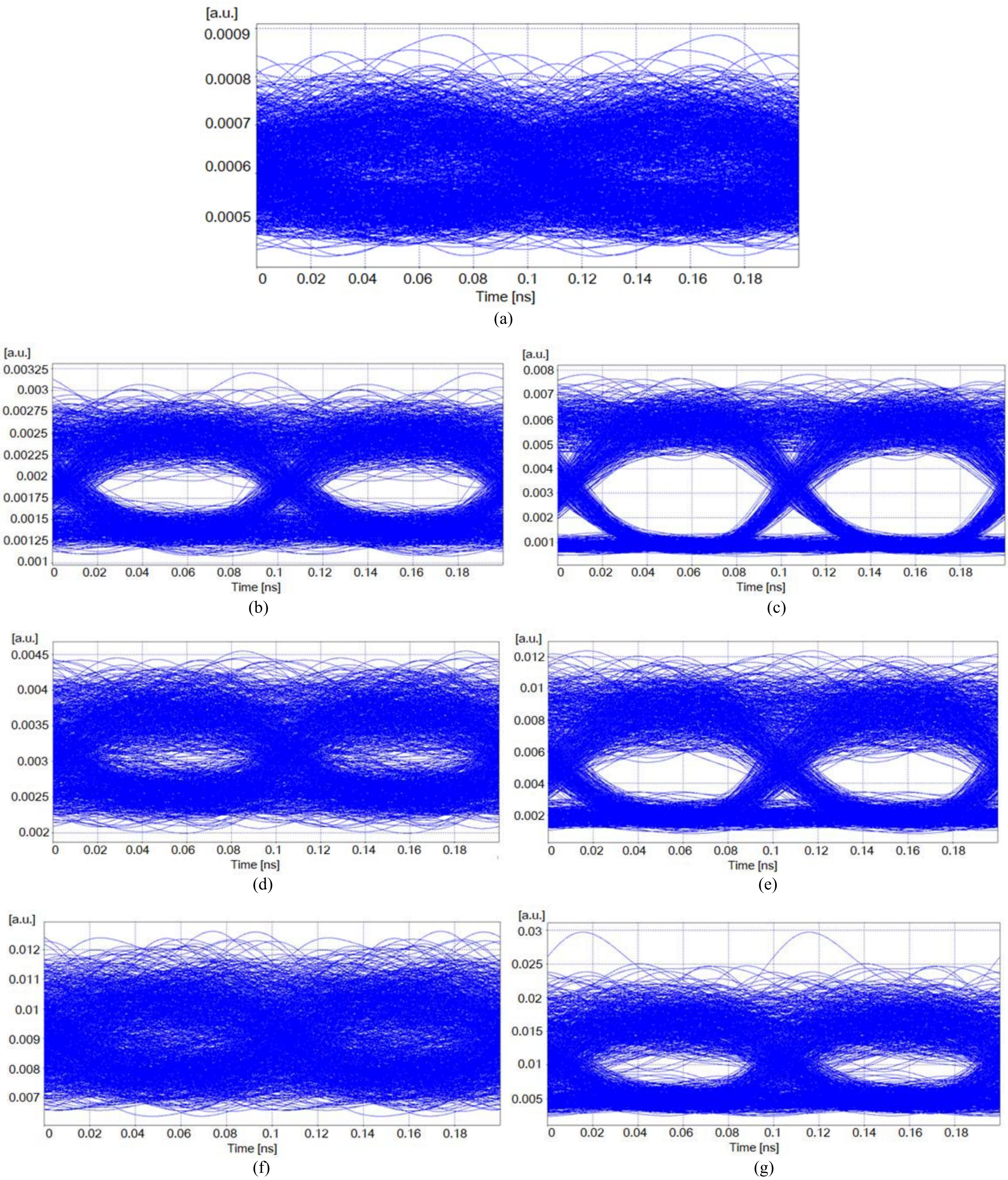


FIGURE 10. Eye diagram. (a) Without DS-EDFA, (b) DS-EDFA at position 1, (c) DS-EDFA at position 1 with interstage OBPF, (d) DS-EDFA at position 2, (e) DS-EDFA at position 2 with interstage OBPF, (f) DS-EDFA at position 3, (g) DS-EDFA at position 3 with interstage OBPF.

for successive EDFAs in the cascade, for transmit power, $P_{avTX} = -20$ dBm. OSNR at the end of the cascade for DS-EDFA placed at position 1, 2 and 3 was 17.37 dB, 14.55 dB and 13.63 dB respectively. Clearly, even with the interstage OBPF included, DS-EDFA at position 1 performs better compared to other positions. But there was also an OSNR improvement in placing DS-EDFA placed at the other positions, especially at position 3.

Fig. 7 (a) and (b) show the OSNR obtained at the end of the cascade over a range of transmitted powers, for the system without and with an interstage OBPF incorporated in DS-EDFA respectively. It can be seen from Fig. 7 (a) and (b)

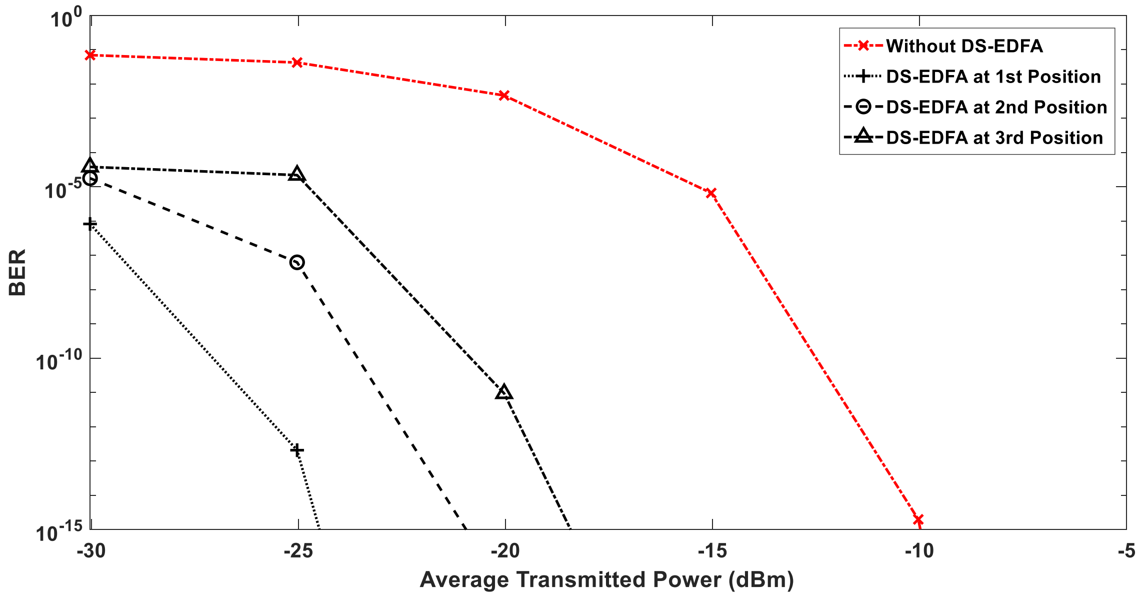


FIGURE 11. BER v/s Average Transmitted Power for a system with cascade of 5 EDFAs.

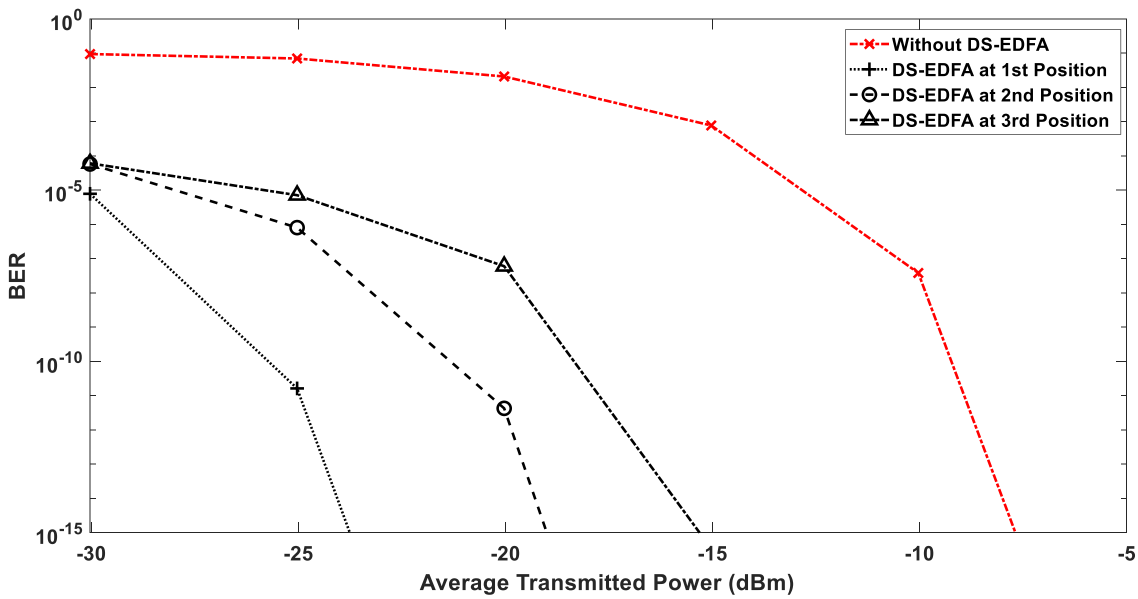


FIGURE 12. BER v/s Average Transmitted Power for a system with the cascade of 7 EDFAs.

that as transmitted power increases, OSNR obtained at the end of cascade increases. However, significant improvement in OSNR can be observed for DS-EDFA incorporating an interstage OBPF and DS-EDFA placed at position 1 provides better OSNR compared to other positions for the entire range of transmitted power. For example, for transmitted power, $P_{\mathrm{avTX}} = -30$ dBm, DS-EDFA without interstage filter at position 1 improves OSNR from 1.6 dB (system without any DS-EDFA) to 3.395 dB and further drastic improvement in OSNR is obtained when an interstage OBPF was used, yielding an OSNR of 10 dB. OSNR measurement and monitoring can help in setting a sufficient margin to deal with other impairments degrading the system performance and it is a standard practice to design a system with OSNR at the end of cascade of at least 20 dB [23]. Thus, here OSNR of 20 dB was obtained for $P_{\mathrm{avTX}} = -10$ dBm and $P_{\mathrm{avTX}} = -15$ dBm for system with DS-EDFA (without an interstage OBPF) and system with DS-EDFA (with an interstage OBPF) at position 1 respectively.

To demonstrate the significance of the interstage OBPF inclusion, the OSNR improvement obtained for the system (measured at the end of the cascade) over the entire range of

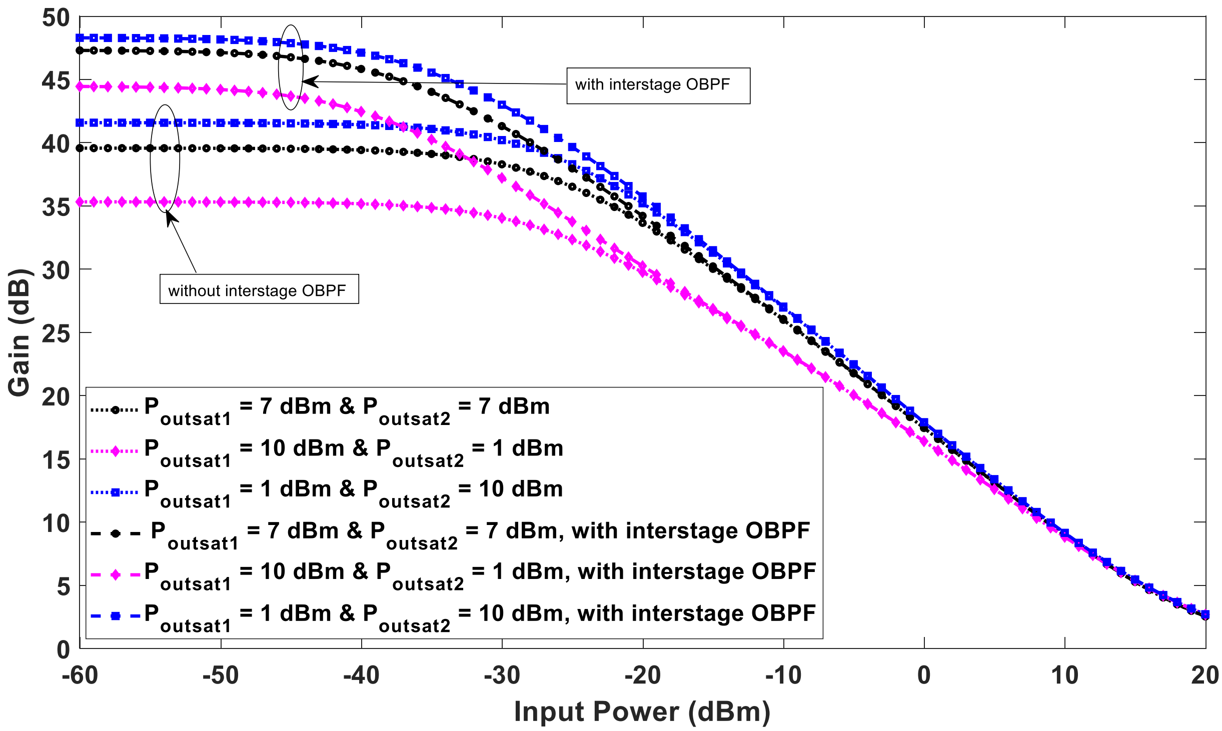


FIGURE 13. Comparison of Gain vs Input Power for different combinations of output saturation power for EDFA1 and EDFA2 of DS-EDFA (with and without interstage OBPF).

transmitted power is shown in Fig. 8. The OSNR improvement is defined as the OSNR (measured at the end of the system cascade) difference between the cases where the DS-EDFA includes and does not include an interstage OBPF. Fig. 8 shows that the OSNR improvement achieved due to the use of the interstage OBPF lies within the 5.4 to 7 dB range for DS-EDFA placed at position 1. Also, as P_{avTX} increases the OSNR improvement increases but gradually starts decreasing on further increase of P_{avTX} due to the saturation of successive EDFAs. For lower P_{avTX}, the OSNR improvement demonstrated here is less reliable because the high ASE noise power results in numerical inaccuracies in locating the signal peak within the optical power spectrum. Thus, there is some error in the OSNR measurements for the systems without an interstage OBPF and this is shown using errors bars (± 0.25 dB) in the figure inset within Fig. 8. The fluctuation in the OSNR improvement values is observed to be the least in case of DS-EDFA placed at position 2 with values falling between 6.13 to 6.82 dB. For the case where the DS-EDFA is placed at position 3 this variation is observed to be between 6.34 to 7 dB.

Fig. 9 (a) and (b) shows the BER evaluated at the receiver using equation (13), for the system with DS-EDFA (without an interstage OBPF) as well as for the same system but with an interstage OBPF included. In both cases, a comparison is also provided with a system without any DS-EDFA. Fig. 9 demonstrates the BER performance improvement when a DS-EDFA is included in the system. However, when no interstage OBPF is used in the DS-EDFA placed at position 3, no significant improvement in BER is observed when compared with the case where DS-EDFA is not used in the system. DS-EDFA placed at position 1 yields the best BER in all cases. For example, when transmitted power, $P_{avTX} = -20$ dBm, BER of 10^{-4} is obtained for system without DS-EDFA, and system with DS-EDFA placed at position 1 yields a BER of 10^{-9} and the BER further decreases less than 10^{-15} when an interstage OBPF is included in DS-EDFA placed at position 1.

Another metric of comparison often used is an eye diagram, which provides a graphical representation of the signal received. The quality of the signal can be judged from the appearance of the eye. Fig. 10 provides the eye diagram comparison for various systems. Here Y-axis represents the power level (in mW) of bit '1' and '0' plotted against simulation run time (in ns) on X-axis. Fig. 10 (a) shows the eye diagram for the case where the system does not feature a DS-EDFA. Fig. 10 (b to g) shows the eye diagrams for the case where the system features a DS-EDFA placed at one of the three positions (as described earlier) in combination with or without an interstage OBPF. It can be clearly seen that DS-EDFA at position 1 has a better eye opening compared to the rest. The impact of using an interstage OBPF on the signal quality improvement, due to reduction of the ASE noise power at the input of EDFA2, is evidenced by the extent of the eye opening seen in Fig 10 (c).

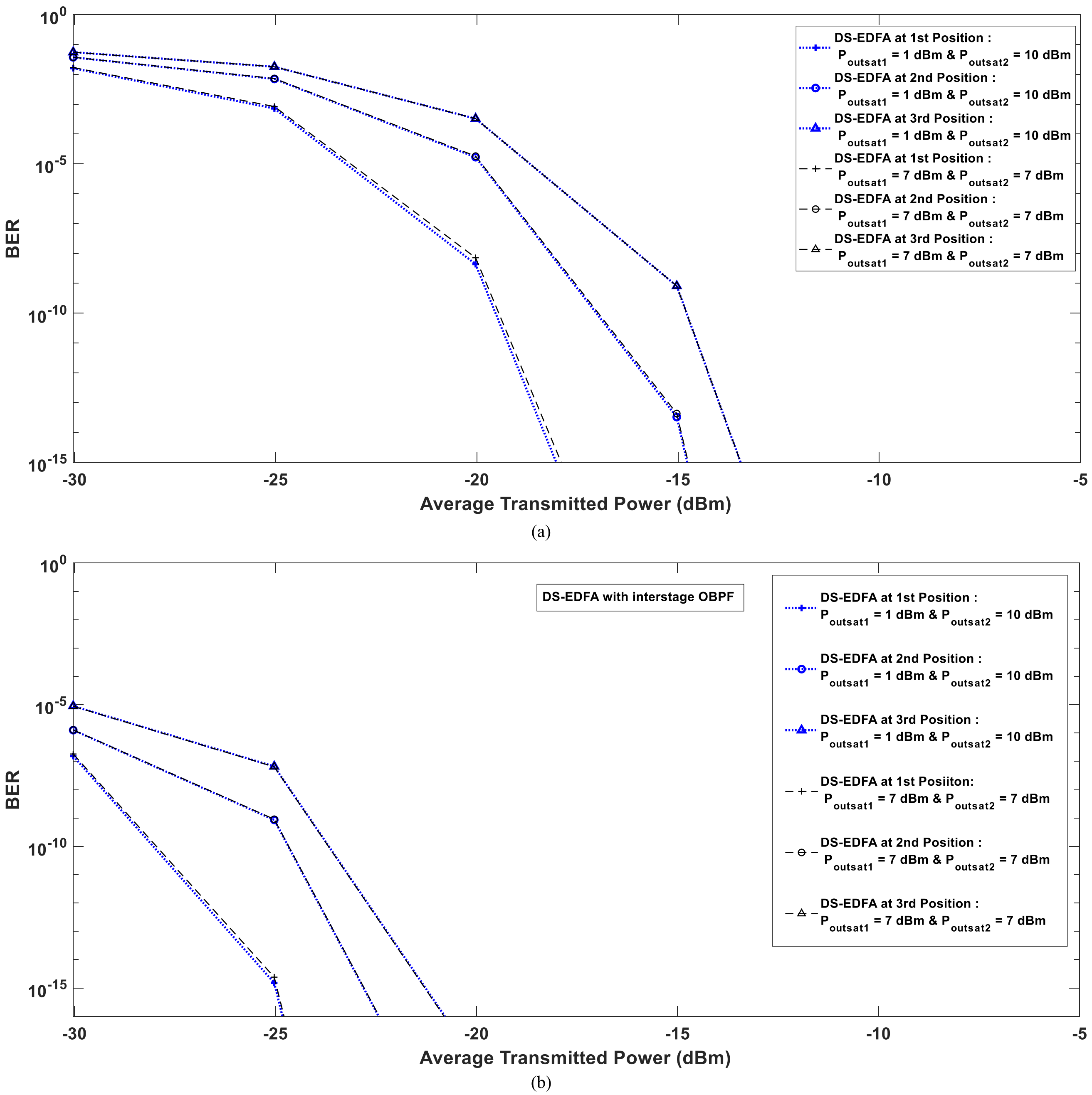


FIGURE 14. **BER vs Average Transmitted Power comparison for different output saturation power for EDFA1 and EDFA2 of DS-EDFA. BER for different placement of DS-EDFA in the system (a) without interstage OBPF and (b) with interstage OBPF.**

B. NUMBER OF EDFAS IN THE CASCADE INCORPORATING SINGLE DS-EDFA

By adding more EDFAs in a FOC system, long-haul transmission is viable. Fig. 11 and 12 shows the BER results obtained for the systems with a cascade of 5 and 7 EDFAs respectively, incorporating a single DS-EDFA (with an interstage OPBF) placed at any of three position as described in section III and depicted in generic system model presented in Fig. 5. Compared to the 3 EDFA system (discussed in section IV-A) that offered a total transmission distance of 375 km, 5 and 7 EDFA systems have total transmission distances of 625 and 875 km respectively. Here, while increasing the total transmission distance, the homogeneity of the inter-amplifier fiber section (each section of 125 km) and EDFAs added to the system is still maintained. Fig. 11 and 12, confirm that the trend of placing of DS-EDFA at position 1 (obtained in section IV-A.) to provide the best BER performance, was unaffected on increasing the total transmission distance. Furthermore, the relative difference between the BER values obtained for DS-EDFA at position 1 and position 2 or between

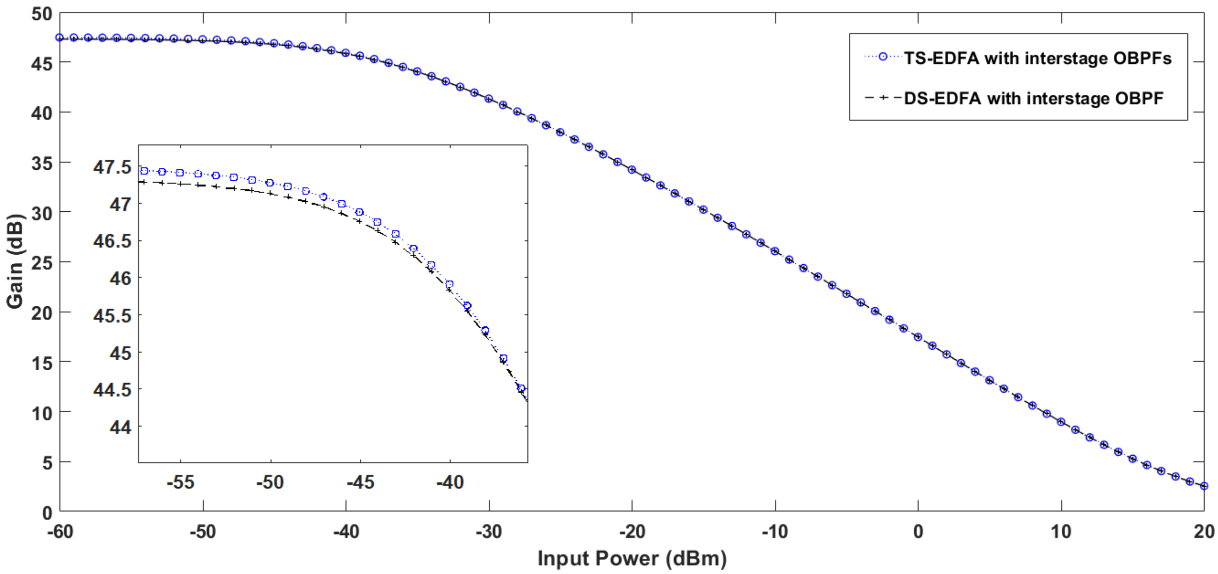


FIGURE 15. Comparison of gain profile of TS-EDFA with two interstage filters and DS-EDFA with one interstage filter.

position 1 and position 3 continues to increase as the transmission distance increases. Adding more EDFAs in the system contributes to increase in ASE noise accumulating at the receiver, and thus DS-EDFA with an interstage OBPF proves advantageous for long-haul system. It can be noted that the performance will continue to improve with the addition of EDFAs to the cascade but not indefinitely due to degrading OSNR (that is brought about by ASE noise accumulation). By incorporating 2R optical regenerators (ORs), the ASE noise accumulation can be reduced which will minimize the OSNR degradation [33]. The number of EDFAs in a cascade will be primarily determined by the minimum OSNR required at the receiver as per system requirements.

C. EFFECT OF OUTPUT SATURATION POWER

In section IV-A and IV-B, the results presented were for a system with the DS-EDFA formed using two identical SS-EDFAs. From previously presented results, it is clear that the signal power obtained at the output of the DS-EDFA has a large impact on the system performance. Thus, in this section the results for DS-EDFA formed using two SS-EDFA with different output saturation power, P_{outsat} are presented. The unsaturated gain G_0 and NF of these two SS-EDFA are the same as mentioned in Table 1. The impact of using different P_{outsat} can be observed in the unsaturated regime of the gain profile of DS-EDFA. Fig. 13 shows the gain vs input power characteristic for different combinations of P_{outsat} for EDFA1 (P_{outsat1}) and EDFA2 (P_{outsat2}) of DS-EDFA with and without incorporating interstage OBPF. Compared with the DS-EDFA formed using two identical SS-EDFAs of $P_{\text{outsat}} =$ 7dBm (see the black curves), the DS-EDFA formed using two SS-EDFAs with $P_{\text{outsat1}} = 1$ dBm and $P_{\text{outsat2}} =$ 10 dBm respectively, provides slightly higher gain (1 dB and 2.02 dB higher with and without interstage OBPF respectively) in the unsaturated regime (see the blue curves). But the DS-EDFA formed using two SS-EDFAs with $P_{\text{outsat1}} =$ 10 dBm and $P_{\text{outsat2}} = 1$ dBm respectively provides lower gain (2.85 dB and 4.25 dB lower with and without interstage OBPF respectively) in the unsaturated regime (see the pink curves). Fig. 13 shows that a DS-EDFA formed using two SS-EDFAs with P_{outsat1} much smaller compared to the P_{outsat2} (here EDFA1 is driven into saturation much earlier compared to EDFA2 i.e. EDFA1 saturating for lower input powers compared to EDFA2) provides slightly higher output gain (and output power) compared to a DS-EDFA formed using identical SS-EDFAs, hence only this combination is further used to investigate its impact on the system performance. Fig. 14 shows the BER comparison for DS-EDFA formed using two SS-EDFAs with $P_{\text{outsat1}} = 1$ dBm and $P_{\text{outsat2}} =$ 10 dBm respectively (see the blue curves) and DS-EDFA formed using two identical SS-EDFA with $P_{\text{outsat}} = 7$ dBm (see the black curves). As the aforementioned gain improvement is small, there is no significant improvement in BER performance using DS-EDFA formed using non-identical SS-EDFAs. Thus, a DS-EDFA formed using two identical SS-EDFAs is more than adequate to meet a target OSNR or BER requirement set for an efficient system performance.

D. TRIPLE STAGE EDFA (TS-EDFA)

Theoretically, there is no restriction on the use of EDFA stages in a multi-stage EDFA design, hence a triple-stage EDFA (TS-EDFA) with same effective gain as DS-EDFA was investigated. Three stages of TS-EDFA were formed using three SS-EDFAs with unsaturated gain of 20, 20 and 10 dB respectively. Other SS-EDFA parameters are the same as that in case of the DS-EDFA mentioned in Table 1.

TS-EDFA also incorporates two interstage OBPFs, same as the ones used in the case of DS-EDFA. Fig. 15 shows the gain vs input power comparison for TS-EDFA with interstage OBPFs and DS-EDFA with interstage OBPF. TS-EDFA has a slightly higher gain for a smaller input power compared to DS-EDFA formed using two identical SS-EDFAs (see the inset in Fig. 15). No significant gain improvement is observed when comparing the gain profile of TS-EDFA with that of DS-EDFA. This is because the signal amplification from the first two stages raises the signal power level to such an extent, that it drives the third stage into high saturation (thereby contributing low gain). Hence, there will be no significant improvement in BER performance of the system. Thus, it can be concluded that using an increasingly higher number of EDFA stages will not prove particularly beneficial to improving system performance beyond what DS-EDFA and TS-EDFA already provide.

V. CONCLUSION

This paper examines the performance of a long-haul FOC system employing a cascade of EDFAs and incorporating a single DS-EDFA (formed using two identical SS-EDFAs) by OptSim simulation and numerical verification using MATLAB. Using identical stages in a DS-EDFA system allows for easier practical implementation and cost-effectiveness (due to ability to use readily available EDFAs) compared to a DS-EDFA system that requires non-identical EDFA devices in each of its stages. Based on the results and analysis described above a conclusion can be drawn that in any configuration, a DS-EDFA incorporating an interstage OBPF is a valuable asset in improving the system performance, as it successfully aids in reducing the ASE noise accumulation. The presented results show that an OSNR improvement of 5.4 to 7 dB can be achieved in the system's OSNR performance by using a DS-EDFA that incorporates an interstage 3nm bandwidth OBPF and this can lead to improvement in the BER performance of the long-haul FOC systems. A comparative investigation between the systems having DS-EDFA placed at three different positions in the system revealed that DS-EDFA placed at position 1 (i.e. at the start of the cascade of EDFAs) offers the best OSNR and BER performance. The presented results also show that as the transmission distance of the long-haul FOC system increases, the impact of DS-EDFA with interstage OBPF on the BER performance of the system increases and is significant even when the DS-EDFA is placed at position 3 (i.e. the end of the cascade). Examining the impact of device characteristics like the interstage OBPF bandwidth, the output saturation power, and the number of stages in the multi-stage EDFA provided an insight on how the system performance can be improved. The presented results show that a DS-EDFA formed using two identical SS-EDFAs and incorporating an interstage OBPF is adequate to ensure a good OSNR and BER performance. Furthermore, a DS-EDFA (with an interstage OBPF) formed with non-identical SS-EDFA (SS-EDFAs with different output saturation powers, $P_{outsat1} < P_{outsat2}$) or TS-EDFA(with interstage OBPFs) do not provide any further significant improvement in the BER performance. Therefore, the use of DS-EDFA incorporating an interstage OBPF of narrow bandwidth (typically, 3 nm or even smaller depending on the system under consideration) is adequate and recommended for long-haul FOC system employing a cascade of EDFAs.

Future Scope: DS-EDFA presented in this paper may be employed in PON to extend its reach. It can also be used in free-space optical (FSO) communication systems to extend their reach and mitigate scintillation caused due to atmospheric turbulence. When applied to a heterogeneous network scenario, DS-EDFA with an interstage narrow OBPF at position 1, will aid in the system performance improvement even if the loss contributed by the preceding fiber section is higher than gain offered by this DS-EDFA. It would be interesting to perform a comparative study on the impact of using different modulation formats for the system presented in this paper. Furthermore, 2R optical regenerators can be incorporated in a long amplifier cascade (consisting of a DS-EDFA with interstage OBPF) to investigate the increased ASE noise accumulation reduction that 2R ORs can offer. As part of future work, it would also be valuable to undertake an experimental validation for the work presented in this paper.

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