OPTIMIZATION OF O-BAND PRASEODYMIUM-DOPED OPTICAL FIBER AMPLIFIER IN A CWDM COMMUNICATION LINK

ABSTRACT

In this paper, a Praseodymium doped fiber amplifier (PDFA) operating in O-band (1276 nm to 1356 nm) is reported. The performance is evaluated by optimizing PDF length, Praseodymium (Pr^{3+}) concentration, its doping radius along with the numerical aperture (NA), pump power and input power to the PDFA in terms of small signal gain and noise figure (NF). Small signal gain >25.23 dB has been observed for the wavelength region of 1276 nm to 1356 nm with a maximum gain of 44.56 dB at 1312 nm. The NF varying in the range of 4.1 dB to 8.2 dB has been obtained. Furthermore, the performance of the PDFA is analyzed in a coarse wavelength division multiplexing (CWDM) transmission link of a fiber-optic communication system at a data rate of 10 giga bits per second (Gbps) as a pre-amplifier based on the quality factor (Q-factor). An errorless transmission with a Q- factor >6 over 90 km of conventional single-mode fiber (SMF) has been achieved.

Keywords - O-Band, Fiber-Optic Amplifier, PDFA

1. INTRODUCTION

Fiber optic communication ensures a dependable and effective pathway for data transmission since the advent of low-loss optical fiber, making it suitable for multi-terabit bandwidth-efficient applications [1]. Over the last few years, network operators have been grappling with a significant upsurge in bandwidth demand attributed to the burgeoning population of internet users across both wired and wireless platforms. This surge stems from the pervasive use of diverse bandwidth-intensive applications in our daily routines, including various social networking platforms, streaming services, web-based gaming, electronic commerce platforms, etc. [2].

For fiber optic communication the two commonly used windows include the 1500 nm and 1300 nm wavelength regions, which exhibit minimal scattering and absorption losses of around 0.22 dB/km and 0.3 dB/km, respectively [3, 4]. Since the conventional 1500 nm window is nearing its capacity limits, it is urgently required to introduce new optical windows characterized by minimal scattering and absorption losses to address the rapid growth in bandwidth demand [5]. In this context, significant attention is being directed towards the exploration of the 1300 nm optical window as a prime candidate for optical communication, owing to its remarkably low overall attenuation of 0.3 dB/km and nearly zero dispersion [6]. Praseodymium is considered as the primary choice for optical transmission systems operating within the 1300 nm window [7]. Praseodymium doped fiber amplifiers (PDFAs) are now commercially accessible amplification in the O-band (1260 nm to 1360 nm) and attracting significant research focus to address bandwidth and capacity challenges in forthcoming optical networks.

Nishida *et al.* [8] developed a PDFA module by connecting two PDFAs in series. They achieved a gain of >10 dB for the wavelength region 1280 nm to 1330 nm at an input power -30 dBm. Since the loss in O-band is relatively high compared to other optical communication bands a high gain of around >20 dB is required for the O-band amplifier in a fiber-optic communication system [2]. Mirza *et al.* [7] analyzed the performance of PDFA through simulation in OptiSystem® solver by optimizing pump power and doping concentration of Pr^{3+}. A maximum small-signal gain of around 22.7 dB at 1300 nm and a minimum NF of 4 dB at 1284 nm were observed for the operating wavelength 1250 nm to 1350 nm. Alharbi *et al.* [9] performed a simulation study to enhance the performance of PDFA with bidirectional pumping by optimizing the length of PDF, the concentration of Pr^{3+}, and its mode-field diameter. A signal gain in the range of around 27 dB to 56.4 dB was observed for the wavelength region 1270 nm to 1350 nm at an input power of -30 dBm and a minimum noise figure of 4.1 dB at an input power of 0 dBm. Although the performance of PDFA presented by Alharbi et al. [9] is better in comparison with the other state-of-the PDFA, the PDFA was pumped bidirectionally with two 1.5 W pump lasers, which is comparatively higher and could be associated

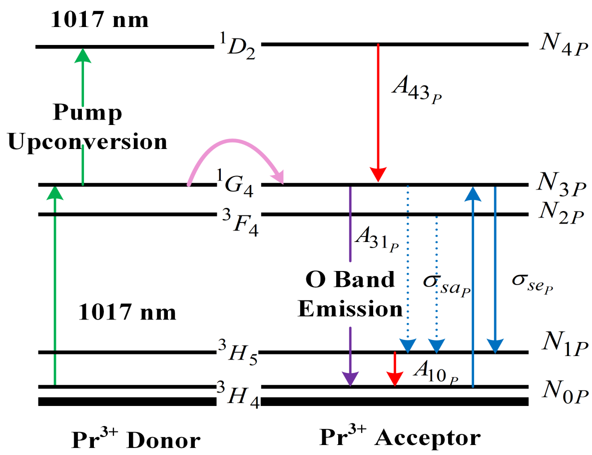

Figure 1 – Energy diagram of Praseodymium ions showing pumping at 1017 nm (green), stimulated absorption and emission in O-band (blue), other radiative transitions (blue dot) donor-acceptor transitions (light-pink) and non-radiative transitions (red).

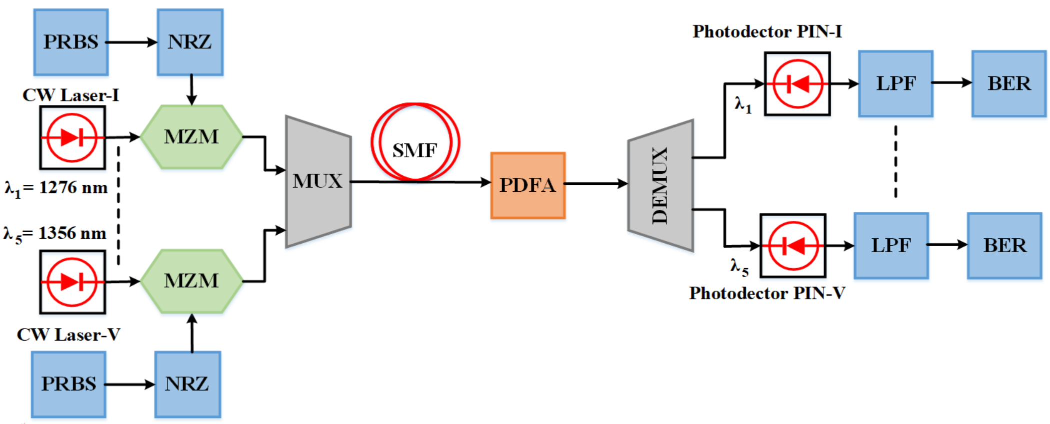

Figure 2 – Diagram illustrating the integration of the PDFA at the system level in a five-channel CWDM transmission system.

with other loss factors owing to thermal modal instabilities [10, 11, 12]. However, the significant variability in the small signal gain of the PDFA, ranging from approximately 24 dB to 56.4 dB, highlights a notable drawback of the amplifier.

In this work, an O-band PDFA has been designed using a 1017 nm wavelength pump at energy levels 3H4 →1G4 →1D2 and emitting in O band (1260 nm-1360 nm) 1G4 → 3H5 as shown in Fig. 1 [7]. Based on the literature survey the novel aspects of our work includes that the proposed PDFA shows a gain >25 dB for the wavelength region 1276 nm to 1360 nm i.e. almost covering the entire O-band with 700 mW pump power using bidirectional pumping. It optimizes all the PDF parameters with gain ranging from 25.23 dB to 44.56 dB and NF ranging from 4.1 dB to 8.2 dB respectively. Again, the transmission performance of the PDFA is evaluated in a CWDM system as a pre-amplifier and offers an errorless transmission over 90 km of conventional single mode-fiber (SMF).

2. SIMULATION SETUP

To evaluate the transmission performance, the PDFA has been optimized and placed as a pre-amplifier in a CWDM system. The schematic illustrated in Fig. 2 consists of five CW lasers of wavelengths 1276 nm, 1296 nm, 1316 nm, 1336 nm and 1356 nm . A pseudo random bit sequence

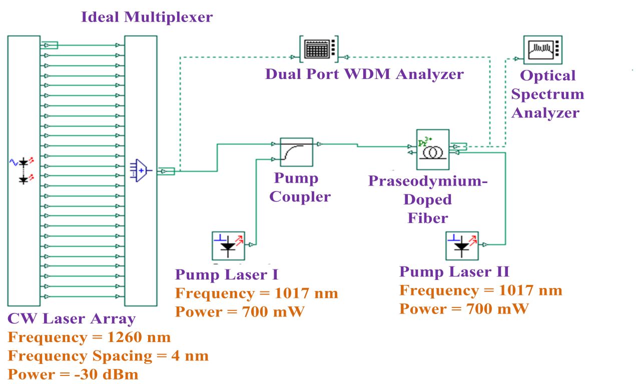

Figure 3 – Simulation Model of the Proped PDFA in OptiSystem®

Table 1 – Optimized value of Simulation Parameters

Parameters	Values
Pumping Wavelength	1017 nm [8]
Pump Power	700 mW
Core Radius	1 μm
PDF Length	27 m
Pr^{3+} Concentration	3×10^{24} m^{-3}
Doping Radius	1 μm
Numerical Aperture	0.38

generator (PRBS) feeds the logical data to the return-to-zero (NRZ) pulse generator which converts it into electrical signal. Subsequently, these electrical signals along with the optical signals emitted by the lasers undergo modulation with a Mach–Zehnder modulator (MZM). Following modulation, the resulting optical signals undergo multiplexing (MUX) and are sent over a conventional SMF.

The combined 50 Gbps CWDM signal, undergoes amplification using the proposed O-band PDFA. At the receiver, a De-multiplexer (DEMUX) is employed to demultiplex the optical CWDM signal. The demultiplexed signals are passed through PIN diodes which are used as photodectors to convert the optical signals into electrical signals. Subsequently, a low-pass Bessel filter (LPF) is applied to reduce band noise and harmonics before the signal is fed into the bit-error-rate (BER) analyzer.

The proposed PDFA architecture for O-band amplification is schematically depicted in Fig. 3. It can be observed that the input signal source comprises a continuous wave (CW) laser array spanning the wavelength range of 1260 nm to 1360 nm, with a frequency spacing of 4 nm and 26 channels, each at a seed power of -30 dBm. The input power is applied to the PDFA via an ideal multiplexer. The PDF is pumped bidirectionally at 1017 nm pumping wavelength with 700 mW pump power. The simulation parameters mentioned in Table 1 are considered to optimize the PDFA using the commercial tool OptiSystem® by Optiwave. A dual port WDM-analyzer has been used to analyze the gain and noise figure (NF) performance of the PDFA.

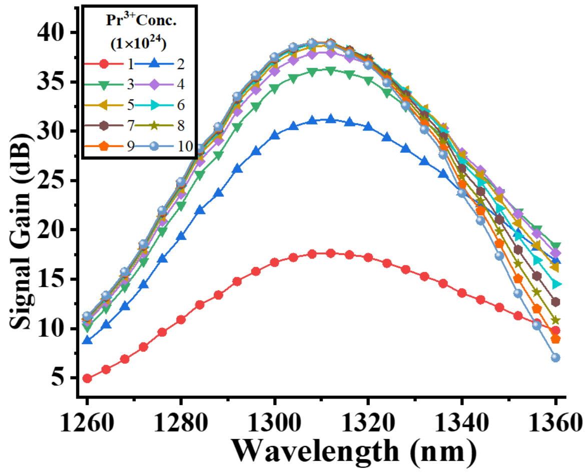

Figure 4 – Variation in signal gain across wavelengths corresponding to different Pr^{3+} concentrations

3. RESULT AND DISCUSSION

In this section, we examine the findings derived from the simulation results of the proposed O-band amplifier module. The evaluation includes analyzing signal gain, bandwidth, noise figure, and Q-factor. The length of the PDF, doping concentration of Pr^{3+}, doping radius, numerical aperture (NA), pump power and input power to the PDFA are optimized to achieve the optimum performance. The optimized values of the parameters are shown in Table 1. Figure 4 illustrates a graph showing how gain varies with signal wavelengths for different Pr^{3+} concentrations, utilizing optimized parameters mentioned in Table 1 across the wavelength range of 1260 nm to 1360 nm. From the plot, in terms of high gain and gain uniformity 3×10^{24} is considered as the optimum doping concentration.

Again, Fig. 5 shows a graph showing the variation of signal gain with signal wavelength for different input power levels within the wavelength range of 1260 nm to 1360 nm. It is observed that the amplifier attains optimum gain performance for the input power -30 dBm. In Fig. 6 the optimized gain and NF characteristics of the proposed amplifier have been

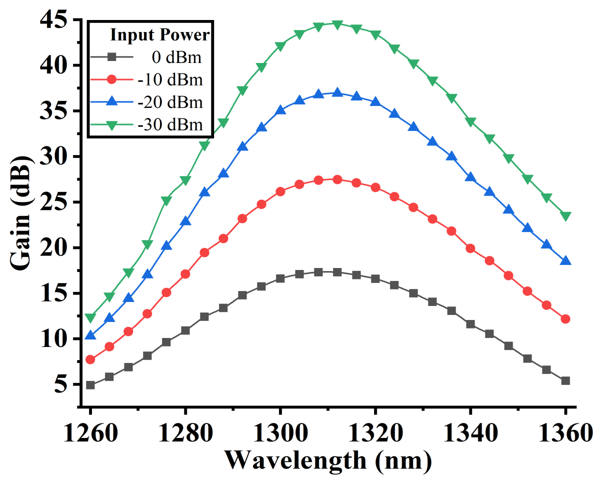

Figure 5 – Variation in signal gain across wavelengths corresponding to different input signal power levels

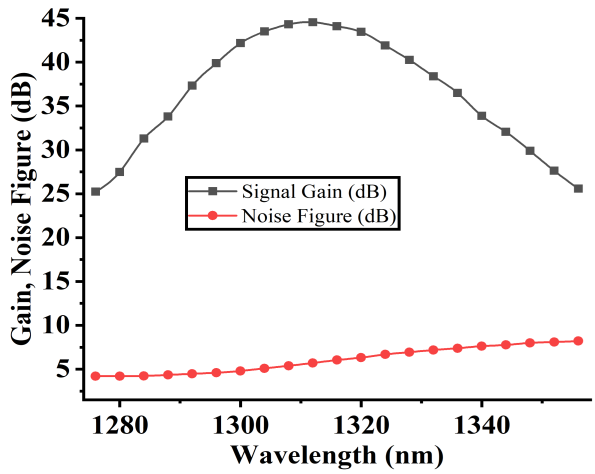

Figure 6 – Optimized performance of signal gain and noise figure across different wavelengths

highlighted with respect to signal wavelength. Notably, a gain ranging from 25.23 dB to 44.56 dB has been observed over a bandwidth of 80 nm (1276 nm to 1356 nm) with a maximum gain of 44.56 dB at 1312 nm. Again it is observed that the NF of the proposed PDFA ranged from 4.1 dB to 8.2 dB across the entire gain band.

To assess the performance of the proposed O-band amplifier within a transmission link, it is integrated into a CWDM system. The Q-factor of the transmitted signals is then measured after the signals pass through a LPF, as depicted in Fig. 2. Figure 7 illustrates the plots of Q-factor versus input power for channels with wavelengths of 1276 nm, 1296 nm, 1316 nm, 1336 nm, and 1356 nm, each operating at a data rate of 10 Gbps. A limited number of channels are chosen for clarity in visualization. It is observed that the system demonstrates optimal performance in terms of Q-factor for the input wavelength of 1276 nm. The variation in Q-factor among different channels is due to the variance in gain for different signal wavelengths. Furthermore, it is observed that the Q-factor increases as the input power increases. Figure 8 displays the plot of Q-factor versus fiber length for various channel wavelengths. The PDFA

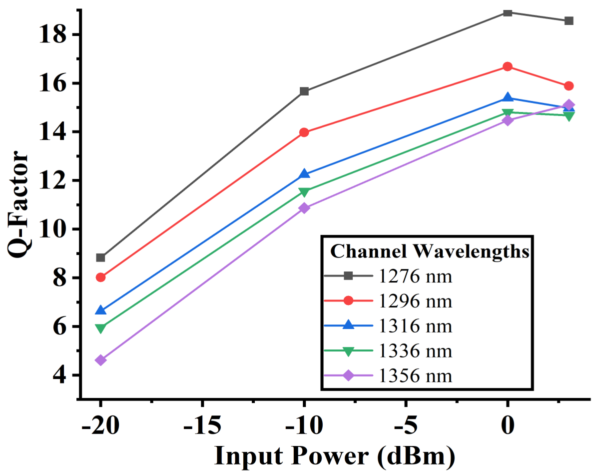

Figure 7 – Quality factor (Q-Factor) as a function of input signal power for five different channels wavelength

Table 2 – Comparison of Pr^{3+} doped O-band optical amplifiers

Authors	**Input Power (dBm)**	**Gain Range (dB)**	**BW** (nm)	G_{max} **(dB)**	**NF Range (dB)**	**Performance Evaluation in Optical Trasmission Link**
Nishida et al. [8]	-30	10-23	1280-1330	23	-	No
Mirza et al. [7]	-30	-	1250-1350	22.7	4-10	No
Alharbi et al. [9]	-30	24-56.4	1270-1350	56.4	5.8-11.5	No
Present Work	-30	25.23-44.56	1276-1356	44.56	4.1-8.2	Yes

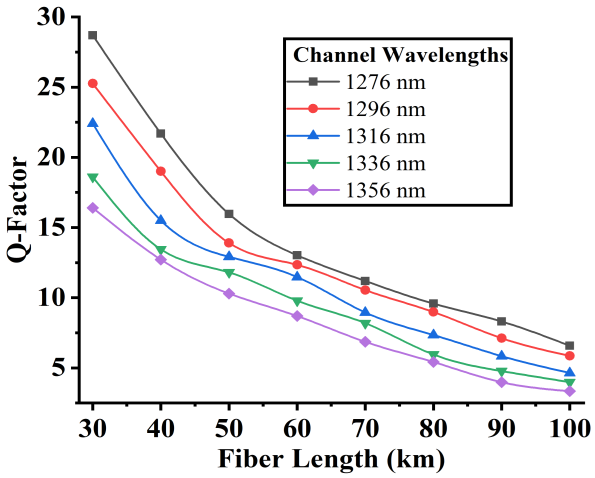

Figure 8 – Quality factor (Q-Factor) as a function of fiber length for five different channels wavelength

achieves a maximum Q-factor of 28.69 for a fiber length of 30 km, which then begins to reduce after 90 km. Despite the differing Q-factor values for different channels, it is noted that the system maintains an acceptable Q-factor of >6 up to a distance of 70 km for all channels.

The performance comparison between the proposed O-band amplifier and existing state-of-the-art schemes has been outlined in Table 2. In this study, a gain exceeding 25 dB across the entire O-band (1276 nm to 1356 nm) has been achieved with a minimum NF variation of 4.1 dB to 8.2 dB for a bandwidth of 80 nm, which represents the best performance compared to the literature sources summarized in Table 2. Also, the study provides a simulation outlook of the proposed PDFA in an optical transmission link of a fiber-optic communication system. Apparently, the proposed amplifier provides errorless transmission up a distance of 90 km of SMF in a CWDM trnsmission link. Therefore, the proposed PDFA offers enhanced efficiency for CWDM transmission in fiber-optic communication systems.

4. CONCLUSION

The performance of Praseodymium doped fiber amplifer is evaluated and demonstrated with the help of simulation results obtained by using OptiSystem® platform. The results show that gain of the PDFA varies between 25.23 dB to 44.56 dB for an input signal wavelength of 1276 nm to 1356 nm of the O-band when pumped bidirectionally at an optimized power of 700 mW. Parametric optimization with length, doping concentration, doping radius, numerical aperture, pump power and input power of PDFA has been performed to optimize the amplifier performance. The NF of the PDFA varies in the range of 4.1 dB to 8.2 dB with a mimimum NF of 4.1 dB at -30 dBm input power. An acceptable Q-factor >6 has been achieved over 90 km transmission while analyzing the PDFA performance in an optical link. The results provide a feasible solution to the bottleneck of the sate-of-the-art C-Band communication using Erbium-doped fiber amplifiers (EDFAs). However, the study lacks the experimental verification which is considered in the future scope of this research.

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