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REGULAR PAPER

Performance evaluation of praseodymium doped fiber amplifiers

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Abstract

In this paper, we report the performance evaluation of praseodymium doped fiber amplifier (PDFA) operating in 1.25–1.35 µm band of wavelengths based on theoretical simulation. The performance of the PDFA is evaluated by considering an optimized length of Pr^{3+} doped fiber, concentration of Pr^{3+} ions and pump power. Moreover, the impact of input signal wavelength on gain, amplified spontaneous emission (ASE) noise and noise figure (NF) of the amplifier is also investigated. A small signal peak gain of around 22.7 dB is achieved at 1.3 µm for Pr^{3+} doped fiber having short length of 15.7 m at an optimized pump power of 300 mW. A minimum NF of 4 dB is observed at 1.284 µm.

Keywords Praseodymium doped fiber amplifier · Small-signal gain · Pump power · Noise figure

1 Introduction

There is a continuous increase in the number of internet users as well as the use of various high bandwidth applications such as voice over IP, video conferencing, online gaming, high definition video streaming and social networking [1, 2]. Consequently, the transmission capacity of optical fiber networks and their reach have enormously increased during the past few years to cope with the huge bandwidth demand. For instance, the recent commercially deployed wavelength division multiplexed (WDM) networks in C-band transport more than 160 channels having aggregate data rate of around 1.6 Tbps over a single fiber of several hundred kilometers in length [3, 4]. Moreover, these WDM networks usually have multiple add-drop sites where certain wavelengths are dropped and added simultaneously with the help of optical add-drop multiplexing components having high optical attenuation [4, 5]. Additionally, the optical signals are further attenuated when transmitted over longer distances. Therefore, the losses are compensated and optical power budget is restored by incorporating the optical amplifiers. Thanks to the development of doped fiber amplifiers that amplify the signal in the optical domain as well as provide a high gain to multiple optical wavelengths simultaneously [6]. Major rare-earth dopants that can potentially be used in the fabrication of doped fiber amplifiers are Erbium, Thulium, Praseodymium and Ytterbium [7].

Generally, optical communication systems operate at those optical windows where optical fiber exhibits low attenuation. The 1.5 µm and 1.3 µm wavelength regions are those two windows where scattering and absorption losses are minimum and are equal to 0.22 dB km^{-1} and 0.3 dB km^{-1}, respectively [8]. As currently most favourite 1.5 µm window faces its capacity limits, opening of a new window is highly desirable to accommodate the exponential growth in demand for transmission bandwidth. Therefore, 1.3 µm window has been widely explored for opportunities by the system

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designers of optical communication systems owing to zero dispersion and low scattering and absorption losses [8, 9]. Praseodymium doped fiber amplifiers (PDFAs) have become commercially available which operate in the 1.25–1.35 µm band, promising the highest gain around 1.3 µm [10].

Doped fiber amplifiers with rare-earth elements such as Erbium, Thulium, Ytterbium, and Praseodymium have been widely researched over the last few decades [4, 6, 7, 10–22]. In Ref. [7], an optimal design of Erbium doped fiber amplifier (EDFA) is proposed where small doping radius is used to achieve best gain performance and efficient pumping. Er^{3+},Yb^{3+} and Pr^{3+} based co-doped fiber amplifiers are proposed in [6, 11, 12] where in Ref. [11, 12] gain performance is evaluated for 1.5 µm and 1.3 µm wavelengths while the authors investigated the control of amplified spontaneous emission (ASE) noise emission from Yb^{3+} ions in Er^{3+}/Yb^{3+} co-doped fiber amplifier in Ref. [6]. An efficient and improved co-doped fiber amplifier having gain medium based on Erbium-Zirconia-Yttria-Aluminium having flat gain of 38 dB with a gain variation of less than 3 dB in 1.53–1.565 µm is proposed [4]. Thulium doped fiber amplifiers (TDFAs) are proposed in Ref. [13–15] having small signal gain of around 41 dB, 45 dB and 30 dB when operating at 1.9 µm, 1.95 µm and 2 µm, respectively. Various efficient designs of PDFAs operating around 1.3 µm are proposed in Ref. [10, 16–18, 21, 22] where the authors in Ref. [10, 16, 21] take up device fabrication related artifacts by considering the impact of temperature variation on Pr^{3+} ions concentration and ASE noise, and maximizing the stimulated emission cross-section by optimizing the Judd-Ofelt parameters, respectively, while gain performance is evaluated in Ref. [17, 18, 22]. Design of broadband mid-IR chalcogenide fiber amplifiers doped with Pr^{3+} ions are proposed in Ref. [19, 20], promising high gain of 25 dB and power conversion efficiency of more than 62.8% while operating at around 4–5 µm and 4.5–5.3 µm, respectively.

Based on the above discussion, we perform a simulation based detailed analysis in this work to optimize the performance of PDFA employing a commercially available software tool called "OptiSystem" from Optiwave Corporation, Ontario, Canada [23]. It has been used to simulate a high-performance optical amplifier by optimizing the Pr^{3+} doped fiber length and pump power under optimized dopant concentration. Therefore, we firmly believe that the proposed design of PDFA will enable the developers to optimize the performance of their end products.

2 Theoretical model of the amplifier

The laser pumping schemes used for doped fiber amplifiers are typically based on the absorption spectrum of dopant ions where the most widely used schemes are in-band and indirect pumping configurations, which can be either in forward or backward direction [13]. In indirect pumping, the pumping wavelength significantly shifts to shorter wavelengths and various processes of energy transfer (cross-relaxation, migration etc) are behind attaining the condition of population inversion at the upper level [24]. In this work we used indirect pumping with forward pumping configuration due to low ASE noise accumulation in input signal when forward pumping is employed.

The four level $^1G_4$ - $^3H_5$ transition of Pr^{3+} ions is represented in energy level diagram of Fig. 1. The spontaneous lifetimes of the energy levels $^1G_4$, $^1D_2$ and $^3P_0$ are represented by τ_3, τ_4 and τ_5, respectively. Pump ground state absorption (GSA) takes place between $^3H_4$ and $^1G_4$ energy levels [25]. Similarly, pump excited state absorption (ESA) takes place between $^1G_4$ and $^3P_0$ energy levels. Signal photons are depleted by the GSA and ESA between $^3H_4$ - $^3F_4$ and $^1G_4$ - $^1D_2$, respectively [25]. Due to cooperative upconversion as a result of ($^1G_4$ - $^1D_2$)-($^1G_4$ - $^3H_5$) transition, the population at $^1G_4$ energy level is decreased [25]. Cooperative upconversion is one such factor reducing the gain because the difference of energy between $^1G_4$ and $^1D_2$ levels is similar to the difference of energy between $^1G_4$ - $^3H_5$ levels. There are two fast non-radiative decays between the first two excited states represented by $^3H_5$, $^3F_4$ and the ground energy $^3H_4$ [25]. Finally, the transition of excited atoms of Pr^{3+} from $^1G_4$ excited state to lower energy level $^3H_5$ yields the required stimulated emission which results in the optical amplification of the signal photons in 1.3 µm wavelength range. Based on energy level diagram shown in Fig. 1, the system can be modeled by the following rate equations for Pr^{3+} ions [25]:

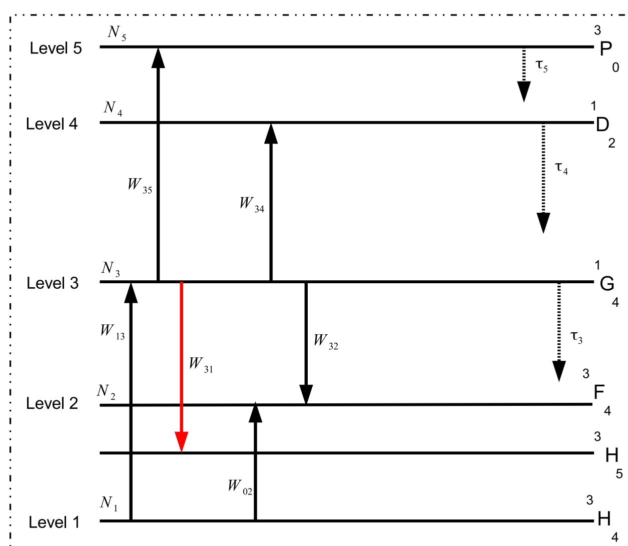

Fig. 1 Energy level diagram of Pr^{3+}

$$\frac{dN_3}{dt} = W_{13}N_1 - \Big(W_{35} + W_{34} + W_{32} + W_{31} + \frac{1}{\tau} + cN_3\Big)N_3 + \frac{B_{43}}{\tau_4}N_4 + \frac{B_{53}}{\tau_5}N_5 \tag{1}$$

$$\frac{dN_4}{dt} = \Big(W_{35} + \frac{c}{2}N_3\Big)N_3 - \frac{N_4}{\tau_4} \tag{2}$$

$$\frac{dN_5}{dt} = W_{35}N_3 - \frac{N_5}{\tau_5} \tag{3}$$

In the above expressions, the transition rates W_{13}, W_{31}, W_{32}, W_{34} and W_{35} are given by $\frac{P_p\sigma_{13}\eta_p}{A_c h\upsilon_p}$, $\frac{P_p\sigma_{31}\eta_p}{A_c h\upsilon_p}$, $\frac{P_s\sigma_{32}\eta_s}{A_c h\upsilon_s}$, $\frac{P_s\sigma_{34}\eta_s}{A_c h\upsilon_s}$ and $\frac{P_s\sigma_{35}\eta_s}{A_c h\upsilon_s}$, respectively. The total population density is given by the following expressions:

$$N_t = N_1 + N_2 + N_3 + N_4 + N_5 \tag{4}$$

where population density N_2 is negligible. Population densities N_1 and N_3 in steady state for $^3H_4$ and $^1G_4$ energy levels are calculated and given by the following expressions.

$$N_1 = \Big(W_{35} + W_{34} + W_{32} + W_{31} + \frac{1}{\tau_3}\Big)\frac{N_3}{W_{13}} + \frac{cN_3^2}{W_{13}} \tag{5}$$

$$N_3 = \frac{\Big[-B + (B^2 - 4AC)^{1/2}\Big]}{2A} \tag{6}$$

where $A = c\Big(\frac{\tau_4}{2} - \frac{1}{W_{13}}\Big)$, $B = 1 + W_{34}\tau_4 + W_{35}\tau_5 + \Big(\frac{W_{35}+W_{34}+W_{32}+W_{31}+\frac{1}{\tau_3}}{W_{13}}\Big)$ and $C = -N_1$. Table 1 elaborates different symbols used in Eq. 1, 2 and 3.

3 Simulation setup

Fig. 2 shows the design of the proposed setup for PDFA. The setup for the amplifier consists of pump laser source, a WDM coupler, a short segment of fiber doped with Pr^{3+} ions, and two optical isolators. The optical isolators in the setup are used for reducing the back reflections which may affect the operation of the amplifier, and stabilizing its operation by preventing it from working as a laser.The gain medium of the PDFA is pumped through a laser source operating at wavelength of λ_p = 1.03 µm and an optimized pump power of 300 mW. Indirect pumping is employed to excite the Pr^{3+} ions in the gain medium of the PDFA by exploiting the shorter wavelengths. The pump at shorter wavelength is typically injected via ground state absorption (GSA) [24], where the peak GSA occurs around the wavelength of 1.03 µm. Since, indirect pumping at shorter wavelengths of 1.01 µm, 1.017 µm, 1.02 µm, 1.03 µm etc have been widely employed in various studies [9, 10, 12, 17, 26], the wavelength of 1.03 µm is chosen as a suitable pump wavelength in our work as well [17]. Consequently, the Pr^{3+} ions in PDFA are excited from ground energy state to higher energy states by forward pumping the gain medium. The photons of the input optical signal that is to be amplified having emission wavelength of λ_s = 1.3 µm interact with the excited Pr^{3+} ions. This results in an increase in energy of the input signal in the form of supplementary photons that are released as a result of stimulated emission of excited Pr^{3+} ions having identical phase and frequency to the photons of the input signal. Dual port WDM analyzer, optical power meter (PM), and optical spectrum analyzer (OSA) are used for monitoring the results and their analysis. The important parameters such as fiber length, doping concentration, pump power, signal power, core diameter, numerical aperture (NA), and mode field diameter (MFD)used in our simulations are summarized in Table 2. These parameters are similar to the commercially available components.

Table 1 Important symbols used in Eq. 1–3

Symbol	Description
τ_3, τ_4, τ_5	Spontaneous lifetimes of $^1G_4$, $^1D_2$, $^3P_0$ levels
N_1, N_2, N_3, N_4, N_5	Ion densities at different levels
c	Cooperative upconversion coefficient
W_{ij}	Transition rate between the i and j levels
P_p	Pump power
P_s	Signal power
σ_{ij}	Stimulated emission cross section between i and j levels
η_p, η_s	Fractional pump and signal powers in doped fiber core
A_c	Doped fiber core area
h	Planck's constant
υ_p, υ_s	Pump and signal frequencies
N_t	Total population density

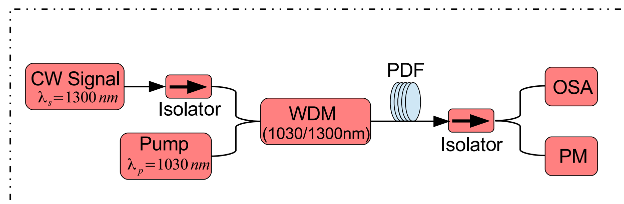

Fig. 2 Schematic of the proposed setup for PDFA, *CW* continuous wave laser, *WDM* wavelength division multiplexing coupler, *PDF* praseodymium doped fiber, *OSA* optical spectrum analyzer and *PM* power meter

Table 2 Important simulation parameters

Sr.No	Parameter	Value
1	Signal wavelength	1.3 μm
2	Pumping wavelength	1.03 μm
3	Optimized pump power	300 mW
4	Core radius	1.2 μm
5	Doping radius	1.2 μm
6	Numerical aperture	0.26
7	MFD	4 μm
8	Signal attenuation	0.1 dB
9	Pump attenuation	0.15 dB
10	Temperature	300 K

4 Results and discussion

The evolution of the gain of the PDFA is observed by varying the Praseodymium doped fiber (PDF) length at different pump powers when the doping concentration of Pr^{3+} ions is 50×10^{24} ions m^{-3}, as shown in Fig. 3a. It may be observed that the PDFA exhibits the highest gain equal to 22.7 dB for 15.7 m length of PDF while using a pump power of 300 mW. A decreasing trend in gain has been observed after further increasing the length of PDF which is due to decrease in population inversion. Therefore, a PDF length of 15.7 m is selected as the optimized length which yields the highest gain. Figure 3b shows the gain versus input signal power plots at different concentrations of Pr^{3+} ions for PDF length and pump power of 15.7 m and 300 mW, respectively. It may be observed that the peak gain is obtained when the doping concentration of Pr^{3+} ions is 50×10^{24} ions m^{-3}.

The power conversion efficiency (PCE) of a doped fiber amplifier can be defined mathematically as [27]:

$$PCE(\%) = \frac{P_{s_{out}} - P_{s_{in}}}{P_p} \tag{7}$$

Where, $P_{s_{in}}$, $P_{s_{out}}$, and P_p are the powers of input signal, amplified signal, and pump respectively. To estimate the PCE of the PDFA which is represented by η, we plot pump power versus output power as a function of input signal power for PDF length and Pr^{3+} ions concentration of 15.7 m and 50×10^{24} ions m^{-3}, respectively. It may be observed from Fig. 4a that maximum value of PCE equal to 12.5% is obtained at input signal power of 0 *dBm* while its minimum value of 0.3% is obtained for input signal power of − 32 *dBm*. The effect of variation of pump wavelength on output power of the amplifier is investigated by plotting the pump wavelength versus output power for an input signal

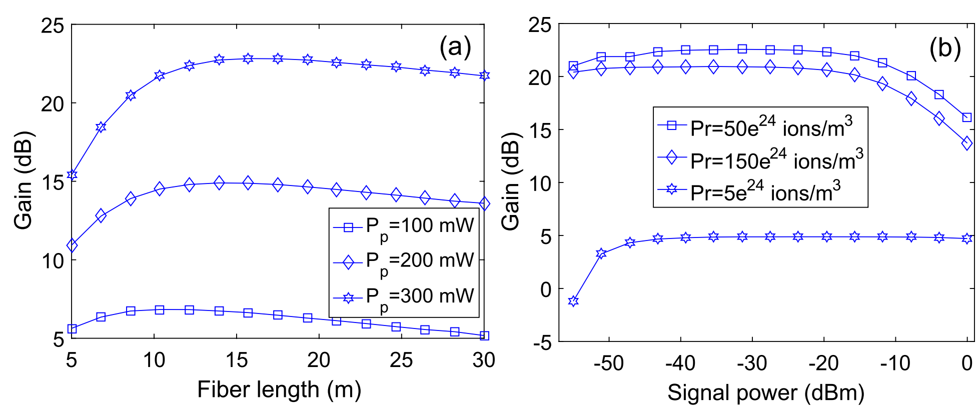

Fig. 3 **a** PDF length versus gain plots for Pr^{3+} ions concentration of 50×10^{24} ions m^{-3} at different pump powers. **b** Effect of different Pr^{3+} ions concentration on the gain of PDFA

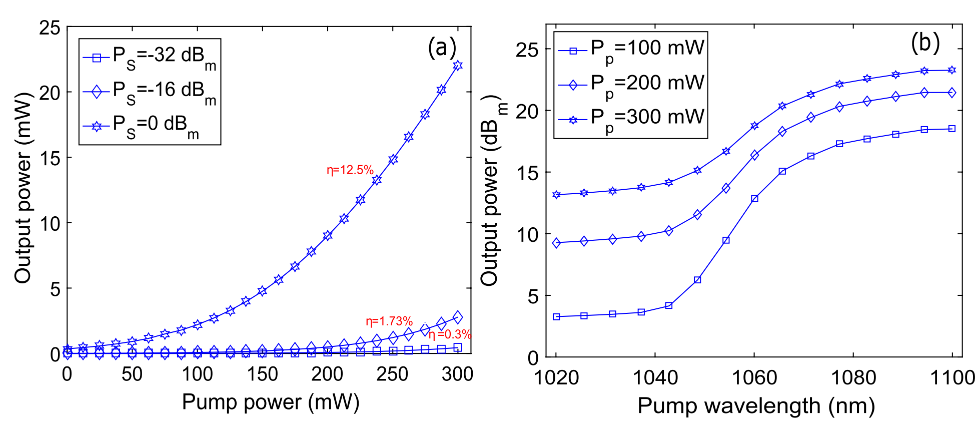

Fig. 4 **a** Pump power versus output power plots at different signal powers. **b** Pump wavelength versus output power plots for an input signal power of 0 dBm at different pump powers

power of 0 *dBm* and different pump powers, as shown in Fig. 4b. It may be noticed that for the wavelength range of 1.02–1.075 µm, the output power starts increasing from values of 3.5 dBm, 10 dBm, and 14 dBm up to 17.3 dBm, 20.3 dBm, and 22.2 dBm for pump powers of 100 mW, 200 mW, and 300 mW, respectively. For the wavelength range of 1.075 µm to 1.08 µm, the output power increases very slowly for each of the three pump power values. For wavelengths beyond 1.08 µm, a saturation region starts where the output power does not increase significantly for the three values of pump powers, as shown in Fig. 4b. The plots of Fig. 4b may be explained by considering the absorption and emission spectra of Pr^{3+} ions [28]. It is evident that absorption spectrum of Pr^{3+} ions lie in the 0.96-1.08 µm wavelength range [28]. Beyond the wavelength of 1.08 µm, there is a gradual decrease in absorption of pump photons, resulting in a decrease in the gain provided by the PDFA. Fig. 5a depicts the ASE spectral plot as a function of pump power obtained at optimized PDF length and Pr^{3+} ions concentration. It may be observed that the ASE peak power is around − 48 dBm at pump power of 100 mW and becomes − 38 dBm at 200 mW of pump power. The highest ASE peak power of around − 31 dB has been obtained at 1.3 µm when the pump power was 300 mW. It is also evident that at higher wavelengths, the PDFA exhibits a decreasing trend in ASE noise power which is due to the impact of GSA at higher wavelengths due to poor inversion [18]. Moreover, 3 dB ASE bandwidth of 35 nm is obtained when the pump power was 300 mW. To find the saturated optical power of the PDFA, gain versus output optical power plots of the PDFA are obtained at different pump powers, as shown in Fig. 5b. Saturated output optical power of 8 dBm and 11 dBm are obtained corresponding to 3 dB points for 200 mW and 300 mW pump powers respectively.

The relation between gain of the PDFA and pump power is investigated by plotting the gain versus pump power at the optimized parameters, as shown in Fig. 6a. It is evident that the gain of PDFA increases by increasing the pump power. The gain dynamics of the PDFA are further elaborated by plotting the gain against input signal power for different pump powers at optimized parameters as shown in Fig. 6b. It may be observed that the lowest gain of 5 dB is achieved at an input signal power of − 30 dBm. The highest gain of around 21 dB is obtained around input signal power of − 30 dBm. On further increasing the power, a sharp decreasing trend in gain of the PDFA up to a lowest value of 13 dB has been observed. The reason behind this particular trend lies in the fact that there are greater number of atoms in lower energy level as compared to excited energy state [11].

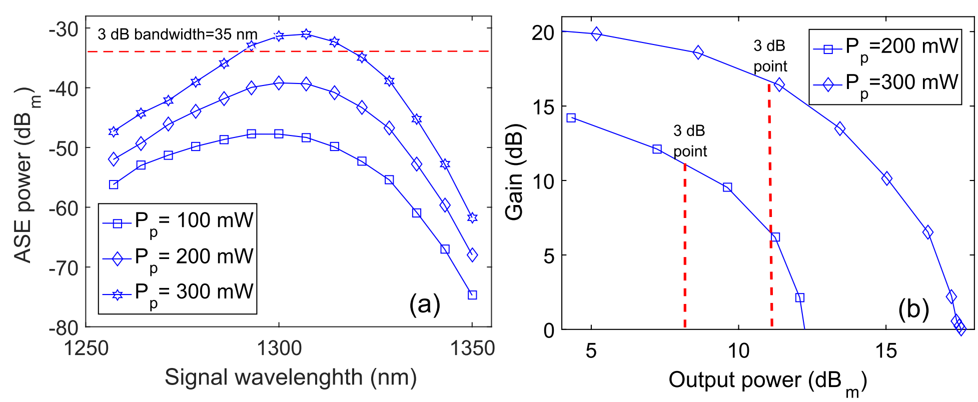

Fig. 5 **a** ASE power versus input signal wavelength plots as a function of pump power. **b** Gain versus output power plots as a function of pump power

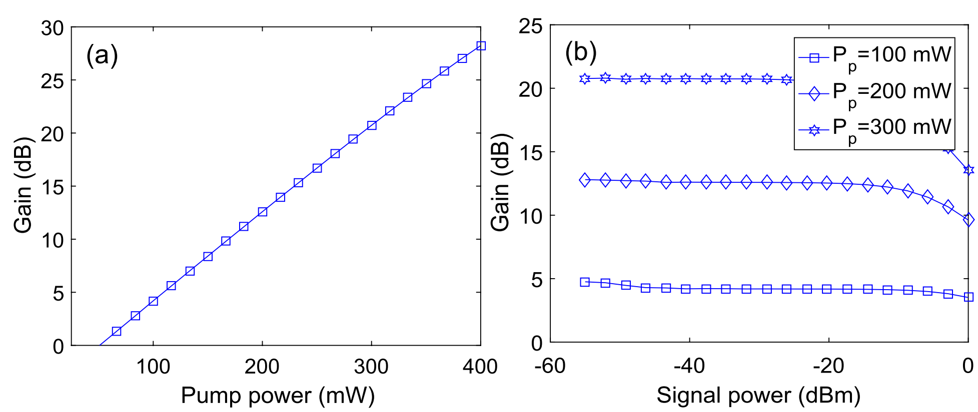

Fig. 6 **a** Gain vs pump power plot at optimized parameters. **b** Gain vs input signal power plot as a function of pump power at optimized parameters

The noise figure (NF) is one of the most important factors used in characterization of the optical amplifiers. NF of an optical amplifier is defined as the ratio of input signal-to-noise ratio (SNR_{in}) to the output signal-to- noise ratio (SNR_{out}) and usually it is expressed in *dB* [29]. Mathematically, it may be expressed as:

$$NF = 10 \log_{10} \frac{SNR_{in}}{SNR_{out}} \quad (8)$$

During the optical amplification of input signal by PDFA, ASE noise generated in the form of photons due to spontaneous emission is added to the signal photons. This ASE noise accumulates with the input signal and reduces the SNR of the amplified signal. Therefore, NF is an important parameter which can efficiently measure the reduction in the SNR of the system. Typically, ASE noise boosts abruptly in the case when the input signal is weak. We have plotted NF of the PDFA against the input signal wavelength and pump power at different input signal powers as shown in Fig. 7. A NF of around 5.1 dB, 5.1 dB and 5.5 dB is obtained at wavelength of 1.3 µm at signal powers of − 32, − 16 and 0 dBm, respectively as shown in Fig. 7a. It may be noticed that a minimum NF of around 4 dB is observed at 1.284 µm corresponding to signal powers of − 32 dBm and − 16 dBm. At the same value of input signal wavelength, NF of around 4.4 dB has been obtained when the signal power is 0 dBm. Similarly, we also have plotted NF of the amplifier versus pump power at different input signal powers as shown in Fig. 7b. It may be noticed that minimum value of NF obtained is around 4.5 when pump power is 0 mW at signal powers of − 32, − 16 and 0 dBm. The reason behind this minimum value of NF is that at 0 mW of pump power, there is negligible amount of ASE which results into high optical signal to noise ratio (OSNR). The values of NF start increasing linearly with pump power up to 100 mW at signal powers of − 32, − 16 and 0 dBm due to increase in amplification as well as ASE. Therefore, the maximum and minimum values of NFs obtained at 100 mW of pump power are around 5.9 dB and 5.6 dB for input signal power of − 32 dB_m and 0 dB_m, respectively. Furthermore, the reason behind slightly higher NF at signal power of − 32 dB_m as compared to 0 dBm is that the input signal of power − 32 dB_m has OSNR already degraded which results into an increase in NF.

Various designs of PDFAs have been proposed by other researchers as already discussed in Sect. 1. To elaborate the superiority of our proposed work, we have compared the important results obtained from this study with results of past studies reported in the literature. Table 3 shows a detailed comparison based on important results between the proposed work and past studies. It may be observed from Table 3 that the proposed optimized design of the PDFA shows better performance than the results obtained in [12, 18, 22].

It may be observed from Table 3 that the small signal gain demonstrated by the authors in Ref. [28] is 30 dB which is apparently higher than the proposed work. The reason behind obtaining the higher gain is that the authors used fluoride based fiber where Pr^{3+} ions were doped while the proposed work considers the glass fiber. The absorption and

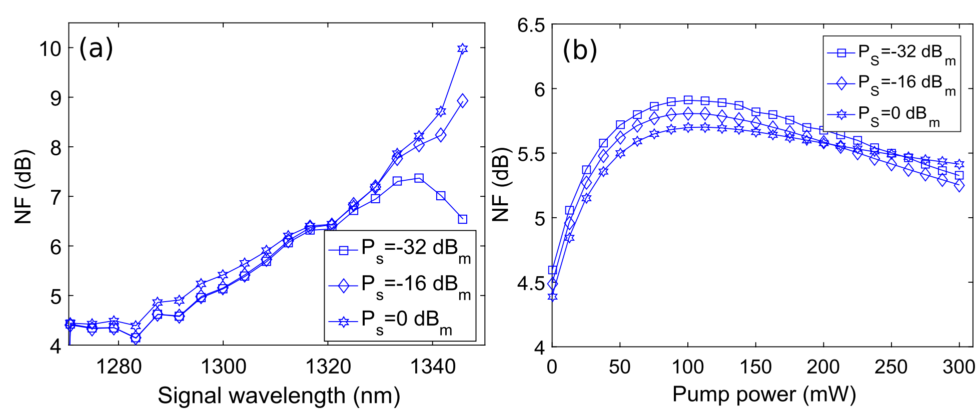

Fig. 7 **a** NF vs input signal wavelength plots at different signal powers **b** NF versus pump power plots at different signal powers

Table 3 Comparison of the important results of the proposed work with results of the past related studies

Study	Wavelength	Gain	NF	Pr^{3+} concentration	Doped length	Core diameter
[12]	1.3 µm	20 dB	–	6×10^{24} *ions* m^{-3}	7 m	5 µm
[18]	1.3 µm	15 dB	–	–	14 m	–
[22]	1.31 µm	20.4 dB	7 dB	–	–	–
[30]	1.3 µm	30 dB	6.5 dB	–	12 m	1.2 µm
[Proposed]	1.3 µm	22.7 dB	4 dB	50×10^{24} *ions* m^{-3}	15.7 m	2.4 µm

emission spectra of Pr^{3+} ions behave differently in fluoride host than glass host. Similarly, the transmission characteristics of optical signals alter in fluoride. Moreover, the authors in Ref. [28] employed dual stage pumping to achieve higher gain while we have employed single forward pump source to obtain gain of 22.7 dB.

5 Conclusion

The performance of Praseodymium doped fiber amplifier is evaluated and demonstrated with the help of simulation results obtained by using OptiSystem software. The results show that a peak gain of around 22.7 dB for input signal wavelength of 1.3 µm is achieved at an optimized length of Praseodymium doped fiber of around 15.7 m when pumped with an optimized power of 300 mW. The minimum NF of 4 dB is obtained at input signal wavelength of 1.284 µm corresponding to signal powers of − 32 and − 16 dBm.

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Declarations

Conflict of interest The authors of this manuscript certify that they have NO affiliations with or involvement in any organization or entity with any financial interest in the materials discussed in this manuscript.

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