Flat-gain optimization of Er-Yb co-doped fiber optical amplifier for ultra-dense DWDM system

DIVYANGNA GANDHI[1,*], SHILPI GUPTA[2]
[1]*Department of Electronics and Communication Engineering, IITE, Indus University, Ahmedabad, 382481, India*
[2]*Department of Electronics Engineering, Sardar Vallabhbhai National Institute of Technology, Surat, 395007, India*

Er-Yb co-doped fiber amplifier has been investigated in this work for the ultra-dense DWDM transmission system. In this work, dominant parameters like fiber length and density concentration of the proposed Er-Yb co-doped fiber amplifier are optimized to achieve the maximum possible flat gain between 1539nm-1563nm wavelengths. This paper also explicates the effects of changing the length and concentration of Er-Yb co-doped fiber to provide the optimum result. It is observed that the gain remains almost flat up to a fiber length of 3m and wavelength between 1539nm-1563nm. Better gain flatness of 0.11dB is perceived at 3m length of the fiber and concentrations of $Er=5\times10^{25}$ m^{-3}; $Yb=6\times10^{26}$ m^{-3}. Furthermore, it is observed that for the low value of density concentration, the difference of gain ripple between 3m and 5m fiber is very less but with an increase in density concentration, the difference of gain ripple increases rapidly. The proposed system has attended higher gain flatness with a very short length of the Er-Yb co-doped fiber compared to other reported systems, making the Er-Yb co-doped fiber amplifier suitable to be incorporated in the long-haul DWDM system because of viability and cost-effectiveness.

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Keywords: Er-Yb co-doped fiber, Gain, Noise figure, BER, Q-factor, WDM

1. Introduction

Nowadays the high data rate optical communication system is demanded from the industries due to rapid growth in internet usage [1]. However, a high data rate not only increased the attenuation losses in the optical fiber but also reduced the SNR which impacted the overall performance of optical communication systems. These dominant factors called for radical changes in the optical communication system. Moreover, the number of users is increasing rapidly.

Therefore, to provide wideband amplification, compensate the fiber losses/ dispersion, and for exploitation of the finest topographies and characteristics of distinct amplifiers the industry has been forced to develop a new optical communication system or improve the performance of the existing system[2, 3]. The performance of the WDM system is mostly determined by data rates, modulation schemes, and amplification techniques.

Optical amplifiers are the need of today's communication networks. Beforehand, the invention of optical amplifiers electronic repeaters was used which includes OEO conversion. However, such regenerators turn out to be costly and quite complex for WDM systems. This diminishes the reliability of networks hence to enhance the overall efficiency and reliability, the use of optical amplifiers came into existence. All channels are amplified at the same time by the deployment of optical amplifiers in WDM networks [4]. Some optical amplifiers have been introduced like semiconductor optical amplifiers (SOA), erbium-doped fiber amplifiers (EDFA), and Raman amplifiers.

These amplifiers are transparent to modulation formats and data rates. So their discovery carried a revolution in optical communication. Among all amplifiers, EDFA is a vital part of every WDM and DWDM system [5], due to many advantages [6-10] was described by numerous researchers to acquire a high gain and low noise figure with 1550nm [11-13].

Simultaneously widespread research has been conducted on new EDFAs by exploiting numerous host and co-dopant materials such as silica, ytterbium alumina, telluride, phosphate, bismuth, and many more to ameliorate the gain enactment, compactness, gain-bandwidth product and curtail the cost of the device [14, 15].

The interesting finding reported that when Yb ions are co-doped with Er ions in the silica glass fiber, a tiny Er-Yb ion-ion separation supplies an indirect pump to erbium and increases the erbium concentration. This decreases the presence of the Er cluster and the up-conversion rate from the upper level of erbium. Thus, acquiring high gain from this co-doped fiber [16-19].

Ytterbium-doped silica fiber, having a broad gain-bandwidth product, high output power, and tremendous power conversion efficiency (up to 80%), proves to be an enormously alluring medium for both the regenerate and the subsequent amplification of ultra-short optical pulses [20-22]. Ytterbium-doped fiber amplifiers have been successfully used for amplifying power at some wavelengths, small-signal amplifiers in fiber sensing applications, material nonlinear optical response, free-space laser communications, and many more applications [23-26].

Sani Mukhtar et al. work on Er^{3+}/Yb^{3+} co-doped fiber amplifier, the design proposed incorporated a short length of 10m co-doped fiber with the optimized pump power of 100mw and achieved a broad-band small-signal gain of 43.5dB. At 1560nm, 4.9 dB of minimum noise figure was perceived [27]. C. Berkdemir et al. achieved 45.4dB of maximum gain when they studied the EYDFA amplifier with various pump power techniques [28]. S. Z. Muhd Yasssin et al. described a higher gain of 56dB with a tolerable noise figure [29] by using a double EYDFA and one pump having a pump power of 140mW.

Alabbas A et al. [30] reported a new wideband and flat gain EDFA amplifier using a newly fabricated hafnia-bismuth-erbium doped fiber and zirconia-erbium doped fiber considering hybrid active fiber for forward and counter pumping schemes. This system has achieved a 14.6dB of gain flatness for a cost of ±1.8dB gain variation over a wide bandwidth of 70nm. The variation of the noise figure is observed between 4.3dB to 7.9dB inside the gain flatness band. Anurupa et.al [31] work on a Raman + EYDFA hybrid amplifier resulted in the attainment of 41.8dB maximum gain with a 15.5dB Q-Factor. For HOA 44.3dB and EYDFA 45.2dB highest flat gain has been obtained. Also, a Q-factor of 14 for HOA and 11.38 for EYDFA have been perceived. Hafiz Muhammad Obaid et al. [32] revealed numerical accomplishment of high and flat gain with EYDFA+ Raman amplifier, attaining flat gain of >26dB with a noise figure of < 4.5dB. O. Mahran [33] proposed study characteristics of 27dBm Er/Yb co-doped fiber amplifier with an obtained gain of 33dB.

In this paper, the proposed novel amplifier has attended more flatness with a very short length of Er-Yb fiber compared to other reported systems by optimizing the performance affecting factors of the amplifier. This analysis has brought various meaningful conclusions regarding the length and density concentration of the Er-Yb co-doped fiber which addresses typical requirements in metropolitan networks with cost-effectiveness.

2. Proposed system model of Er-Yb co-doped fiber amplifier

The system of the proposed Er-Yb co-doped fiber amplifier is depicted in Fig. 1 with forward pumping of 1480 nm wavelength and 200 mW pump power. All the 120 channels available at the output of transmitters are equally spaced with the spacing of 0.2nm (25GHz) between 1539 nm-1563 nm wavelengths having input signal power of 0.1-3 mW. NRZ intensity modulation is used to modulate the data of 10Gbps and afterward, data are multiplexed by wavelength division multiplexer (WDM). These channels first pass through a 150km span of single-mode fiber and then through the Er-Yb co-doped fiber amplifier.

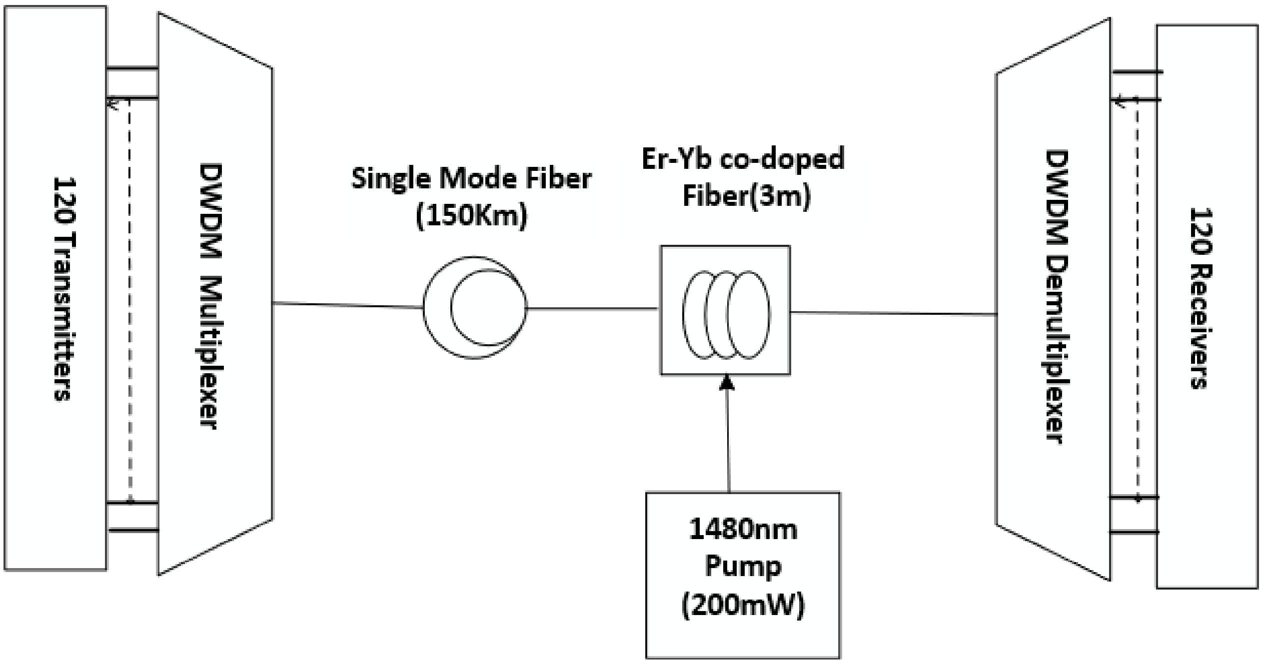

Fig.1. Schematic representation of the proposed Er-Yb co-doped fiber amplifier

Table 1. WDM system parameters

Parameters	Value
No. of channels	120
Data rate (Gbps)	10
Modulation type	NRZ
Channel spacing	0.2nm
Input signal power	0.1- 3mw
Channel length	150km +3m

Table 2. Parameters of Er-Yb co-doped fiber

Parameters	Value
Length of fiber	0.5 to 8m
Radius of core	1μm
Pump power	200mW
Wavelength of pump	1480nm
Numerical aperture	0.31
Cross-section area	50μm^2
Ions density (Er^{3+})	$5.1\times10^{25}m^{-3}$
Ions density (Yb^{3+})	6.20×10^{26} m^{-3}
Pump loss	0.1dB/m
Signal loss	0.1dB/m
Lifetime of Er^{3+}	10 ms
Lifetime of Yb^{3+}	1.5 ms

These amplified channels are de-multiplexed by DWDM and these separated channels are forwarded to the relevant receiver. The PIN detector with 0.9A/W of responsivity and 1nA dark current is used at the receiver side for the detection of signals. Parameters reported in Table 1 and Table 2 are used to simulate the system performance as depicted in Fig. 1.

The performance of the proposed Er-Yb co-doped fiber amplifier has been analyzed by considering gain, noise figure, average gain, Q-factor, BER and gain flatness. Moreover, the effect of changing the length and density concentration of Er-Yb co-doped fiber has been analyzed.

3. Results and discussion

The gain and noise figure of the proposed Er-Yb co-doped fiber amplifier is illustrated in Fig. 2 as a function of channel wavelength over a range of 1539 to 1563nm.

The total gain of the signal for the EYDFA amplifier is defined below.

$$G_{EYDFA}(z) = \frac{Ps(z)}{Ps(o)} = \left[\frac{Pp(z)}{Pp(o)} exp\left[\tau_p z\left(\sigma_{13}N_{Er} + \sigma_{45}N_{Yb}\right) - \alpha\tau_s\sigma_{12}N_{Er}z\right]\right]^{\frac{1}{\alpha}} \quad (1)$$

Where parameter α is defined as

$$\alpha = \frac{\tau_p\sigma_{13} + \tau_{p(}\sigma_{45}+\sigma_{54)}\left(\frac{1-\eta_0}{\eta_0}\right)}{\tau_{s(}\sigma_{12}+\sigma_{21)}} \quad (2)$$

EYDFA length is z, the power of the pump and signal in the steady-state are P_p and P_s, and signal and pump overlapping factors are τ_s and τ_p. The cross-section of signal absorption and signal emission are σ_{12} and σ_{21}, the cross-section of pump emission is σ_{54}, and the cross-section of pump absorptions are σ_{45} and σ_{13}. The total ion concentrations of Er^{3+} and Yb^{3+} are N_{Er} and N_{Yb}.

$$\eta_0 = \frac{N_2}{N_2+N_3} \quad (3)$$

Concentrations of E_2 and E_3 states of Er^{3+} ions are N_2 and N_3 respectively.

In this analysis, 0.1 mW input signal power and 3m length of Er-Yb co-doped fiber are used. From Fig. 2, it can be observed that the gain increases as wavelength increases and 37.93dB highest gain is achieved at 1558.4nm wavelength, beyond this wavelength the gain again starts to decrease. Also, it shows the noise figure varies between 4.32 to 5dB during the entire range between 1539 to 1563nm.

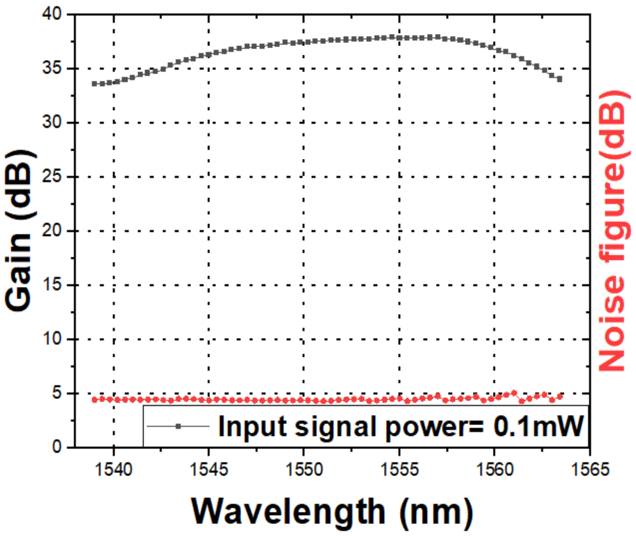

Fig. 2. Gain and noise figure spectrum of Er-Yb Co-doped fiber amplifier (color online)

To observe the effect of gain by changing the length of the Er-Yb co-doped fiber amplifier, the system has been investigated. In this investigation, length of Er-Yb co-doped fiber is varying between 0.5 - 8m while keeping other Er-Yb co-doped fiber amplifier parameters the same as given in Table 2. Fig. 3 represents the variation of gain with wavelength for different lengths of Er-Yb co-doped fiber. It can be noted that 40.33dB highest gain is obtained for the length of 8m fiber with 1560.8nm wavelength. Also, it is seen that up to a length of 3m the gain remains almost flat with very less amount of ripple throughout the entire range. Nevertheless, a further increase in Er-Yb co-doped fiber length provides an extremely high ripple.

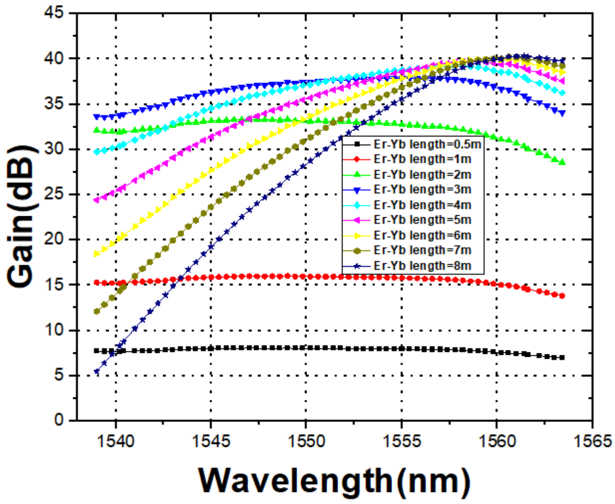

Fig. 3. Gain of Er-Yb co-doped fiber amplifier as a function of different lengths of Er-Yb co-doped fiber (color online)

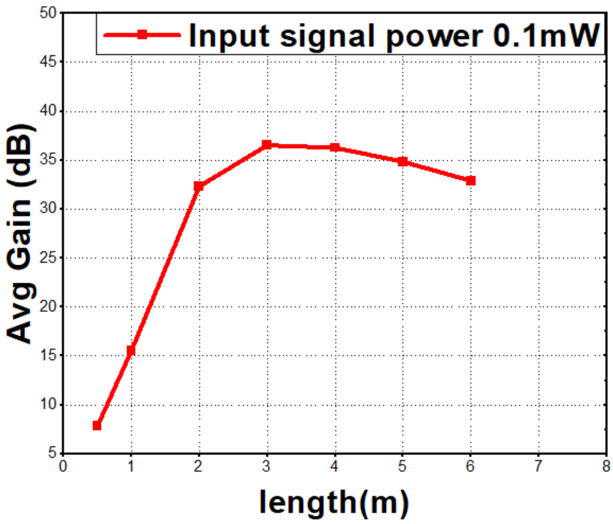

Fig. 4. The average gain of Er-Yb co-doped fiber amplifier for different lengths of Er-Yb co-doped fiber (color online)

The average gain with Er-Yb co-doped fiber length has been shown in Fig. 4. The peak average gain of 36.5dB is achieved at a 3m length. The lowest average gain of 7.8dB is noticed at 0.5m length and it rises to 36.5dB at 3m, after that gain again falls up to 33dB.

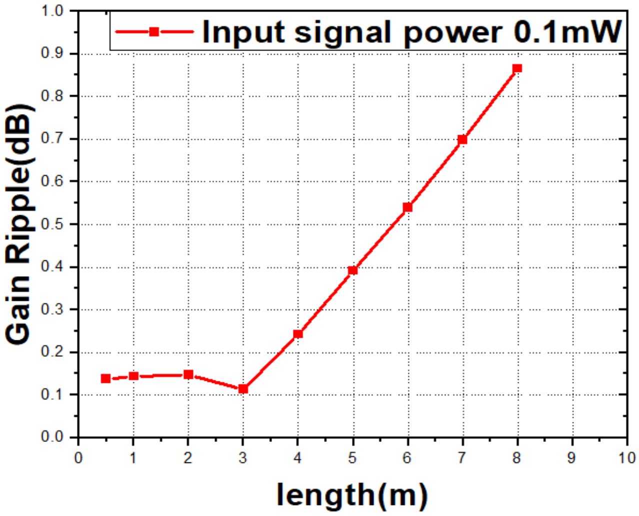

Fig. 5. A gain ripple of Er-Yb co-doped fiber amplifier for different lengths of Er-Yb co-doped fiber (color online)

A gain ripple of Er-Yb co-doped fiber amplifier for 1539 to 1563nm wavelength has been shown in Fig. 5 with Er-Yb co-doped fiber length. It has been observed that the lowest gain ripple of 0.11dB is achieved at the 3m length of the fiber. Beyond 3m, the gain ripple is increased as length increases, and a peak gain ripple of 0.86dB is reported at 8m length of the fiber.

Fig. 6 illustrates the gain behavior of 3m length of Er-Yb co-doped fiber for 1539 to 1563nm wavelength with the variation of input signal power between 0.1-3mW. The highest flat gain of 37.93dB is achieved at 1558.4nm wavelength using 0.1mW input signal power. While an increase in input signal power from 0.1mW to 3mW, the gain starts to decrease and the ripple starts to increase.

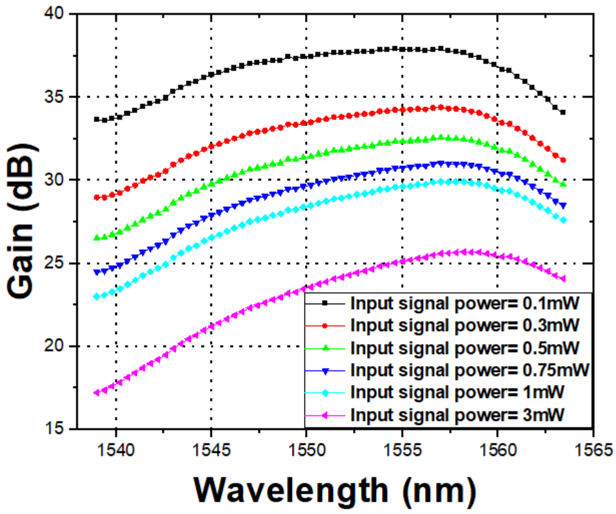

Fig. 6. Gain spectrum of Er-Yb co-doped fiber amplifier as a function of input signal power (color online)

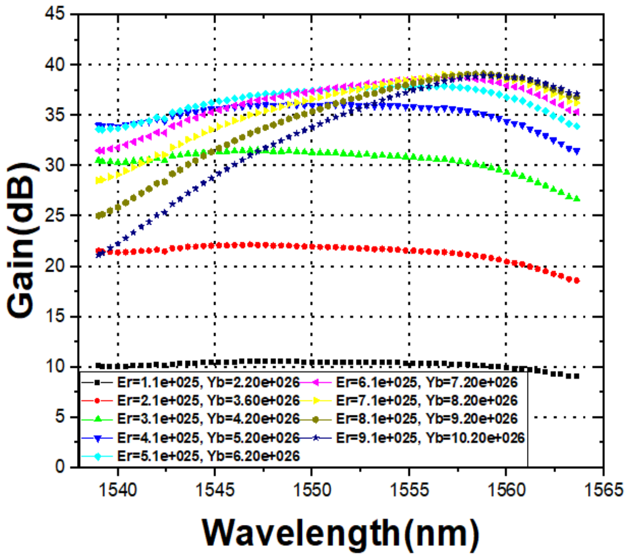

Fig. 7. Gain of Er-Yb co-doped fiber amplifier as a function of different Er-Yb co-doped fiber concentrations with 3m length of Er-Yb co-doped fiber (color online)

From Fig.7, it has been noticed that 39.14dB maximum gain with 0.36dB ripple is provided at 1558.8nm wavelength with a concentration of Er=8.1 × 10^{25} m^{-3} and Yb=9.20×10^{26} m^{-3}. If the concentration is further increased, the gain is dropped with a very high ripple. On the contrary, it has been observed that the lowest gain ripple of 0.11dB with 37.93dB maximum gain is observed at Er=5.1×10^{25} m^{-3} and Yb=6.20×10^{26} m^{-3} concentration.

From Fig. 8, it has been shown that 39.91dB maximum gain with 0.7dB ripple is provided at 1560.8nm wavelength with concentrations of Er=7×10^{25} m^{-3}; Yb=8×10^{26} m^{-3}. If the concentration is further increased, the gain is dropped with a high ripple. On the other hand, it has been observed that the lowest gain ripple of 0.12dB with 37.95dB maximum gain is observed at Er=3×10^{25} m^{-3}; Yb=4×10^{26} m^{-3}.

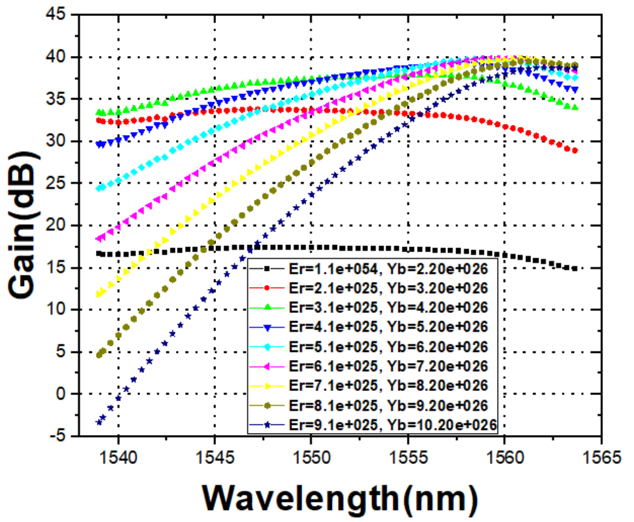

Fig. 8. Gain of Er-Yb co-doped fiber amplifier as a function of different Er-Yb co-doped fiber concentrations with 5m length of Er-Yb co-doped fiber (color online)

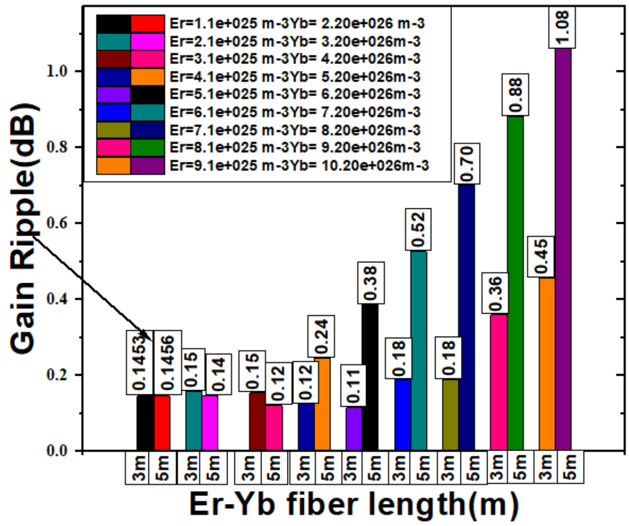

Fig. 9. Comparison of gain ripple with 3m and 5m fiber length as a function of different densities of Er-Yb co-doped fiber (color online)

From Fig. 7 and Fig. 8, it can be concluded that as the length of Er-Yb co-doped fiber increases from 3m to 5m, ripple increases.

Fig. 9 represents a comparison of gain ripple with 3m and 5m fiber length as a function of different densities of Er-Yb co-doped fiber. It is observed from Fig. 9 that for the lower value of density concentration the difference of gain ripple between 3m and 5m fiber is very less but with an increase in density concentration the difference of gain ripple between 3m and 5m fiber increases rapidly.

Fig. 10 illustrates the Q-factor of 3m length of Er-Yb co-doped fiber concerning wavelength. The highest Q-factor of 7.7dB is obtained at 1543.4nm wavelength.

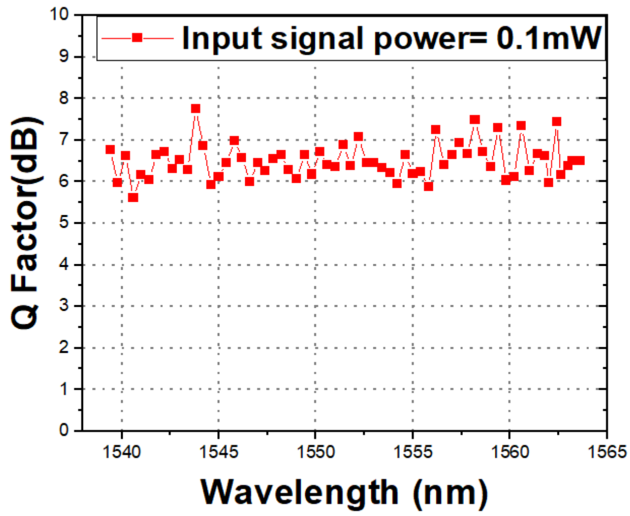

Fig. 10. Q-factor of Er-Yb co-doped fiber amplifier as a function of wavelength (color online)

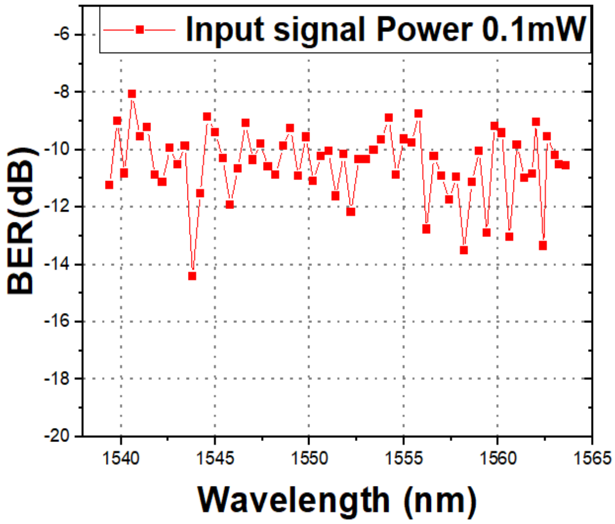

Fig. 11. BER of Er-Yb co-doped fiber amplifier as a function of wavelength (color online)

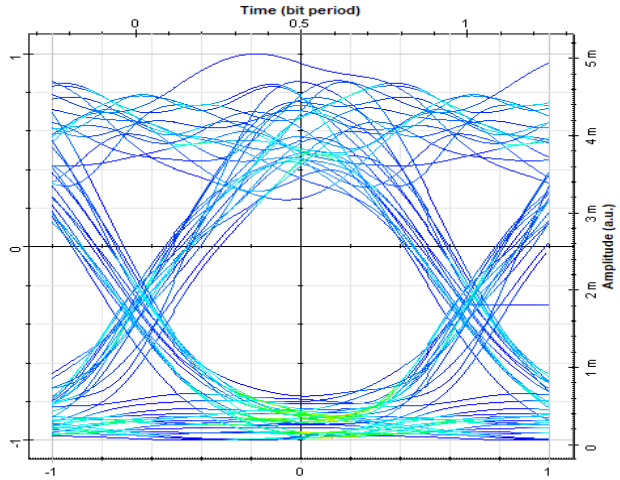

Fig. 12. EYE diagram of EYDFA amplifier (color online)

Fig. 11 presents the BER of 3m length of Er-Yb co-doped fiber concerning wavelength and it can be observed that BER increases from 3.83×10^{-15} to 1.77×10^{-09}.

Fig. 12 shows the EYE diagram of the simulated system measured at the receiver.

Table 3. Summary of gain ripple for 3m and 5m length of the fiber with density variation

Density of Er ions Density of Yb ions	1.1×10^{25} m^{-3} 2.2×10^{26} m^{-3}	2.1×10^{25} m^{-3} 3.2×10^{26} m^{-3}	3.1×10^{25} m^{-3} 4.2×10^{26} m^{-3}	4.1×10^{25} m^{-3} 5.2×10^{26} m^{-3}	5.1×10^{25} m^{-3} 6.2×10^{26} m^{-3}	6.1×10^{25} m^{-3} 7.2×10^{26} m^{-3}	7.1×10^{25} m^{-3} 8.2×10^{26} m^{-3}	8.1×10^{25} m^{-3} 9.2×10^{26} m^{-3}	9.1×10^{25} m^{-3} 10.2×10^{26} m^{-3}
Gain ripple (dB) for 3m length of fiber	0.1453	0.15	0.15	0.12	0.11	0.18	0.18	0.36	0.45
Gain ripple (dB) for 5m length of fiber	0.1456	0.14	0.12	0.24	0.38	0.52	0.70	0.88	1.08

Table 3 represents that 0.11dB maximum gain flatness is attended with 3m fiber length as compared to 5m fiber length. Also, it shows that fiber length and concentration increases ripple also increases

4. Conclusion

An Er-Yb co-doped fiber amplifier is proposed and investigated for a 120×10 Gb/s DWDM system at a channel spacing of 0.2nm over a wavelength range of 1539-1563nm. Optimizing the parameters of the proposed amplifier allows a gain of 37.93dB and a noise figure of 4.32dB with 0.1mW input signal power. With the increase in input signal power beyond 0.1mW the fall in gain and increase in ripple are observed.

This paper also elucidates the effects of changing the length and concentration of Er- Yb co-doped fiber, resulting in the maximum flatness of 0.11dB at a 3m short length of Er-Yb fiber and concentrations of Er=5×10^{25} m^{-3} Yb=6×10^{26} m^{-3} compared to other listed systems in the comparison table (Table 4) after that high ripple is observed. It is also observed that for the low value of density concentration the difference of gain ripple between 3m and 5m fiber is very less but with an increase in density concentration, the difference of gain ripple increases rapidly. Results obtained by optimizing the parameters confirm the viability and cost-effectiveness of the proposed amplifier for long-haul DWDM communication applications. Future work can be extended to flatten and broaden the gain spectrum of Er-Yb co-doped fiber amplifier by using a fiber-based (Long-period Fiber Gratings) gain flattening method and a different hybrid combination.

Table 4. Comparison of the proposed system with other published works

Specification	1. Anurupa et al.(2019) [31]	2. Anurupa et al. (2021) [34]	3. Hafiz Muhammad Obaid et al. (2019)[35]	4.O.Mahran (2016)[33]	5. Sani Mukhtar et al.(2019) [27]	6. Simranjit Singh et.al (2014)[36]	7. Simranjit Singh et.al (2013)[37]	Present work (Er-Yb co-coped amplifier)
Amplifiers	EYDFA	EYDFA	EYDFA	EYDFA	EYDFA	HA+DRA-EDFA	Two stages DRA-EDFA	EYDFA
No. of channels	100	100	100	47	-	100	160	120
Data rate(Gbps)	80	80	10	-	-	10	10	10
Channel spacing nm(GHz)	[0.2 (25)]	[0.2 (25)]	[0.2 (25)]	-	-	[0.2(25)]	[0.2(25)]	0.2 (25)]
Channel Length	150km(SMF) + 5m(Er-Yb fiber)	150km(SMF) + 5m (Er-Yb fiber)	75km(SMF) +1m(Er-Yb fiber)	0.7-1m(Er-Yb fiber)	10m(Er-Yb fiber)	-	-	150km(SMF) +3m (Er-Yb fiber)
Gain Ripple(dB)	0.16	0.16	-	-	-	1.15dB	<4.5	0.11
Bandwidth in (nm)	32/100 (1535–1567) (1525–1625)	32/100 (1535–1567) (1525–1625)	20 (1545-1565nm)	85 (1525-1610nm)	1540nm,1550nm, 1560nm	20nm	34nm (1569-1603nm)	24 (1539-1663nm)
Input Power	0.1-2.5mW	0.1-2.5mW	1mW	-30dbm	-40dbm	-20dbm	-	0.1-3mW
Pump wavelength, Pump Power	1056/1480nm, 200mW	1056/1480nm, 200mW	1056nm, 100mw	980nm, 300mw	1480nm, 100mw	-	-	1480nm, 200mW

Abbreviations: EYDFA, Erbium-Ytterbium co-doped fiber amplifier

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*Corresponding author: divya.gandhi123@gmail.com