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Achieving high gain using Er-Yb codoped waveguide/fiber optical parametric hybrid amplifier for dense wavelength division multiplexed system

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Abstract. A hybrid optical amplifier is proposed using a combination of Er-Yb codoped waveguide amplifier (EYDWA) and fiber optical parametric amplifier (FOPA). The scheme is investigated for 100×40 Gb/s dense wavelength division multiplexed (DWDM) system at 0.2-nm channel spacing. The parameters are optimized to achieve a flat gain of >30.6 dB, with a gain ripple of 2.67 dB. This is obtained over a wavelength range of 1542 to 1562 nm at −10-dBm optimum input power per channel, without using any costly gain flattening scheme. For higher input powers up to 10 dBm, an increase in gain ripple from 2.67 to 6.13 dB is observed. The gain ripple of 2.67 dB of the proposed EYDWA–dual pump FOPA configuration is also much better than 10.32 dB for the hybrid EYDWA–single pump FOPA. The obtained high and flat gain, along with the low noise figure, confirms the usefulness of the proposed amplifier for applications in long-haul DWDM systems. [DOI: 10.1117/1.OE.57.5.056108]

Keywords: hybrid optical amplifier; dense wavelength division multiplexed; Er-Yb codoped waveguide amplifier; fiber optical parametric amplifier; flat gain.

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1 Introduction

A rapid growth in high-speed internet and the demanded data rate significantly enhances the requirements for transmission bandwidth of dense wavelength division multiplexed (DWDM) systems.[1,2] Existing systems are rapidly approaching their capacity limits.[3] This requires high capacity DWDM systems, with higher and flattened gain. The gain flattening over a given wavelength range for the conventional optical amplifiers is limited because of its dependence on the signal wavelength and width of radiating energy bands.[4] In this scenario, a hybrid optical amplifier is a viable option to play a key role,[5,6] as these offer the required gain bandwidth, simultaneously providing a flat gain.[7,8]

The optical waveguide amplifiers are typically fabricated on a planar substrate, thus exhibiting the advantages of a compact structure with an integration capability. The active and passive components are combined on the same substrate, resulting in small footprint and low production cost.[9] A high gain for DWDM systems can be achieved using waveguide amplifiers. However, several factors like better gain flatness, among integrated DWDM channels still need more attention.[10] Yeh et al.[11] proposed the optical gain-clamped erbium-doped waveguide amplifier (EDWA) using forward optical feedback technique. Di Pasquale et al.[12] demonstrated a longitudinal multimode pumping scheme for the Er-Yb codoped waveguide amplifier (EYDWA). They reported a gain of 4 dB per centimeter using high-power broad area lasers, being pumped at around 980 nm. They also suggested the possibility of integration of low-cost amplifiers having applications in WDM metropolitan networks.

Fiber optical parametric amplifier (FOPA) is mainly composed of one or two parametric pumps and highly nonlinear fiber (HNLF). The amplification process is based on the nonlinear phenomenon of four wave mixing (FWM) occurring in HNLF.[13,14] The FOPA can be designed to operate in the desired wavelength range by appropriate tuning of the pump wavelengths, pump powers, and parameters of HNLF.[14] FOPAs have attracted significant attention in the recent past for DWDM systems due to their capabilities to provide high gain bandwidth and low noise figure (NF).[15–17] Jazayerifar et al.[17] have derived the analytical expressions for the FOPA-based DWDM system and confirmed the feasibility of FOPAs as in-line amplifiers for broadband long-haul DWDM systems.

Owing to the importance of the issue, many efforts on hybrid optical amplifiers have been reported in the past to fulfill high gain bandwidth requirements of DWDM systems.[6] Hasan et al.[18] transmitted 40×40 Gb/s DWDM signals, over a distance of 80 km, with 50-GHz spacing, using differential phase shift keying modulation format. They evaluated the system and economic impacts of Raman amplification and the two different hybrid Raman–Erbium-doped fiber amplifier schemes. Singh and Kaler[19] demonstrated a hybrid combination of EYDWA and semiconductor optical amplifier to achieve flat gain for 100×10 Gb/s DWDM system at channel spacing of 0.2 nm. They reported a flat gain of >14 dB over 1554- to 1574-nm wavelength range. Stephens et al.[20] experimentally demonstrated the amplification of 10×58 Gb/s, 100-GHz spaced signals using hybrid Raman-FOPA. They achieved gain improvement of 5 dB for the Raman-FOPA by appropriate tuning of the pump wavelength and power

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when compared with the individual contributions of parametric and Raman pumps. They recommended Raman-FOPA as an attractive proposal for future long-haul communication systems.

In this paper, an EYDWA–FOPA hybrid amplifier is proposed and investigated for 100-channel DWDM system at reduced channel spacing of 0.2 nm. Higher gain, with small variations, is achieved without using any costly gain clamping component, thus making it useful to address typical requirements in metropolitan networks. This paper is organized in five sections. After introduction, the performance measures of the proposed hybrid configuration are defined in Sec. 2. The proposed model is described in Sec. 3, followed by the discussion of results in Sec. 4. Finally, Sec. 5 summarizes the conclusions.

2 Performance Measures of Proposed Hybrid Amplifier

Any configuration of multiple optical amplifiers in a single transmission link is known as hybrid optical amplifier. These hybrid configurations combine different optical amplifiers to fulfill high gain bandwidth requirements of DWDM systems.[18]

The total signal gain for EYDWA is the ratio of signal power after length L to the input signal power, and it is calculated as[21,22]

$$G_{\mathrm{EYDWA}} = \frac{P_s(L)}{P_s(0)} = \left\{ \frac{P_p(L)}{P_p(0)} \exp[\Gamma_p L(\sigma_{13} N_{Er} + \sigma_{45} N_{Yb}) - \alpha \Gamma_s \sigma_{12} N_{Er} L] \right\}^{\frac{1}{\alpha}}, \tag{1}$$

where parameter α is defined as

$$\alpha = \frac{\Gamma_p \sigma_{13} + \Gamma_p(\sigma_{45} + \sigma_{54})\left(\frac{1-\eta_o}{\eta_o}\right)}{\Gamma_s(\sigma_{12} + \sigma_{21})}, \tag{2}$$

where $P_s(0)$ and $P_P(0)$ are the input signal and pump power levels, respectively, N_{Er} and N_{Yb} are the total Er^{3+} and Yb^{3+} ion concentrations, respectively, σ_{12} and σ_{21} are, respectively, the Er^{3+} absorption and emission cross-sections; σ_{45} and σ_{54} are, respectively, the Yb^{3+} absorption and emission cross sections, σ_{13} is the Er^{3+} absorption cross section, Γ_s and Γ_p are, respectively, the overlapping factors of the signal and pump, and η_o is the initial energy transfer efficiency.

The signal gain for the dual pump FOPA is given as[23]

$$\mathrm{G_{FOPA}} = 1 + \left[2\gamma \frac{\sqrt{P_1 P_2}}{g} \sin h(g.L)\right]^2, \tag{3}$$

where γ is nonlinear coefficient of HNLF and L is the length, P_1 and P_2 are the parametric pump powers, and g is parametric gain coefficient given as

$$g = \sqrt{4\gamma^2 P_1 P_2 - \left(\frac{k + \delta k}{2}\right)^2}, \tag{4}$$

where k is phase mismatch defined as

$$k = \beta_2 \omega_c (\Delta\omega_s^2 - \Delta\omega_P^2) + \frac{1}{12}\beta_4 \omega_c (\Delta\omega_s^4 - \Delta\omega_P^4) + \gamma(P_1 + P_2), \tag{5}$$

where $\omega_c = \frac{\omega_1+\omega_2}{2}$, $\Delta\omega_s = \omega_s - \omega_c$, and $\Delta\omega_P = \omega_1 - \omega_c$. Also, ω_1 and ω_2 are the frequencies of two pumps providing gain to a signal at frequency ω_s with a phase, which can be determined from the phase mismatch k given in Eq. (5). β_2 and β_4 are second- and fourth-order dispersion coefficients, respectively.

The overall gain and effective NF of hybrid configuration are influenced by the individual optical amplifiers. The total gain (in dB) is the sum of the gains of the individual cascaded amplifiers.[24] Therefore, the overall gain of proposed hybrid amplifier can be computed as

$$G_{\mathrm{overall}}(\mathrm{dB}) = G_{\mathrm{EYDWA}}(\mathrm{dB}) + G_{\mathrm{FOPA}}(\mathrm{dB}) - T_c(\mathrm{dB}), \tag{6}$$

where T_c is the overall insertion loss for the signals.

The NF of n'th stage of amplification in a transmission system can be approximately computed using the equation [25]

$$NF_n = \frac{2P_{ASEn}}{B_o h v G_n} + \frac{1}{G_n}, \tag{7}$$

where P_{ASEn} is the amplified spontaneous emission (ASE) noise power, G_n is the gain, hv is the photon energy, and B_o is optical resolution bandwidth.

The overall NF of n-stage cascaded system is given as[26]

$$\mathrm{NF_{overall}} = \mathrm{NF_1} + \frac{\mathrm{NF_2} - 1}{G_1} + \frac{\mathrm{NF_3} - 1}{G_1 G_2} + \cdots\cdots + \frac{NF_n - 1}{G_1 G_2 \cdots G_{n-1}}, \tag{8}$$

where G_n and NF_n are the gain and NF of n'th stage, respectively. It can be observed from Eq. (8) that the cascaded NF is mostly influenced by the NF of amplifiers, closest to the input of the system. The first amplifier has most significant effect, and the NF of subsequent stages is reduced by the positive stage gains. So, if only loss is present in the cascade, then the overall NF equals the magnitude of the total loss. In case of a two stage, EYDWA–FOPA hybrid amplifier, Eq. (8) reduces to

$$\mathrm{NF_{overall}} = \mathrm{NF_1} + \frac{\mathrm{NF_2} - 1}{\mathrm{G_1}} = \mathrm{NF_{EYDWA}} + \frac{\mathrm{NF_{FOPA}} - 1}{\mathrm{G_{EYDWA}}}. \tag{9}$$

The Q-factor and bit error rate (BER) are used as a measure of the transmission quality and degradation in a system. The Q-factor is defined as[18]

$$Q = \frac{\langle I_1 \rangle - \langle I_0 \rangle}{\sigma_1 + \sigma_0}, \tag{10}$$

where $\langle I_1 \rangle$; and $\langle I_0 \rangle$; are the mean photocurrents for ones and zeros, respectively. The parameters σ_1 and σ_0 are the respective standard deviations of the photocurrents. The BER can be obtained from the Q-factor using the relationship[26]

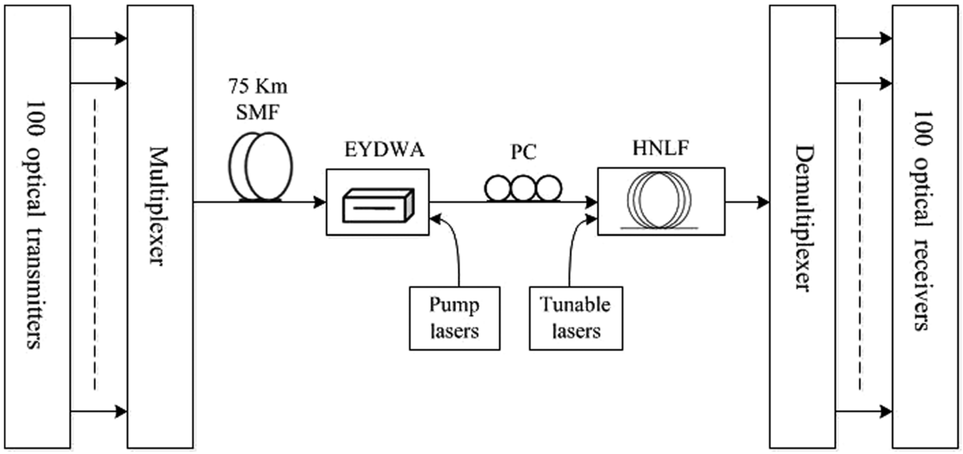

Fig. 1 Schematic of proposed setup for EYDWA–FOPA hybrid optical amplifier.

$$\mathrm{BER} = \frac{1}{2}\,\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right), \tag{11}$$

where erfc is the complementary error function.

3 Proposed Setup

The schematic of the proposed setup, shown in Fig. 1, consists of 100 DWDM, 0.2-nm spaced channels covering the 1542- to 1562-nm wavelength range using continuous wave (CW) lasers. The channels are driven by the data stream from 40 Gb/s, nonreturn-to-zero modulated signals with input power of −10 dBm each. In the given model, signals are transmitted over 75-km span of single mode fiber before they get amplified by the proposed hybrid configuration. The PIN photodetector with a responsivity of 0.9 A/W and dark current of 1 nA is used at the receiver side.

The proposed hybrid amplifier is characterized via simulation in conjunction with OptiSystem and MATLAB. Optimization processes have been carried out to select optimized parameters for the hybrid configuration to achieve high gain with better gain flatness.[9,27,28]

For EYDWA–FOPA hybrid amplifier, the signal enters the EYDWA stage before it is fed to the cascaded FOPA for further amplification. A 980-nm counterpropagating

Table 1 Parameters of EYDWA.

Parameter	Symbol	Value
Waveguide length	L	0.07 m
Er^{3+} ion density	N_{Er}	2×10^{26} m^{-3}
Yb^{3+} ion density	N_{Yb}	2×10^{27} m^{-3}
Er^{3+} absorption cross section	σ_{12}	6.5×10^{-25} m^2
Er^{3+} emission cross section	σ_{21}	9×10^{-25} m^2
Er^{3+} absorption cross section	σ_{13}	2.58×10^{-25} m^2
Yb^{3+} absorption cross section	σ_{45}	1×10^{-24} m^2
Yb^{3+} emission cross section	σ_{54}	1×10^{-24} m^2
Pump overlap factor	Γ_p	0.921
Signal overlap factor	Γ_s	0.795
Initial energy transfer efficiency	η_o	0.115

Table 2 Parameters of FOPA.

Parameter	Value
HNLF length	500 m
HNLF nonlinear coefficient (γ)	15.029 W^{-1} km^{-1}
HNLF attenuation	0.6 dB/km
HNLF dispersion slope	0.02 ps/nm^2 km
Zero dispersion wavelength of HNLF	1552 nm
Parametric pump wavelengths and powers, two pumps	1540.9 nm ($P_1 = 0.8$ W)
	1563.1 nm ($P_2 = 1.2$ W)

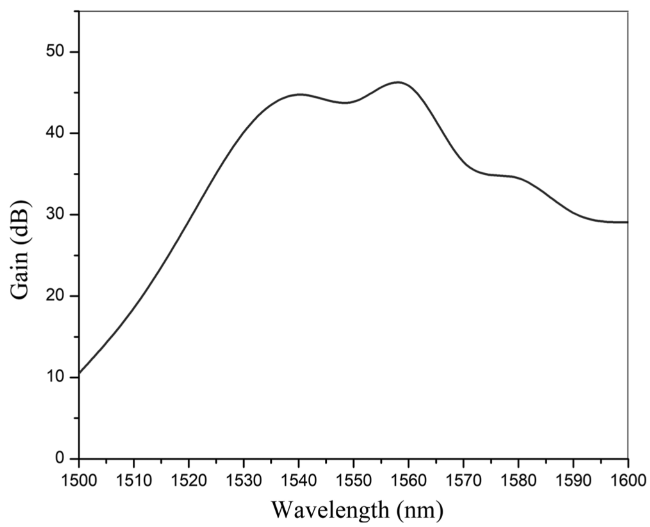

Fig. 2 Gain profile of EYDWA–FOPA hybrid optical amplifier for 1500- to 1600-nm wavelength range.

pump at 450-mW power is used to pump EYDWA. Optimized EYDWA parameters to obtain large gain are listed in Table 1.[10,22] In case of FOPA, copropagating pumps and signals are combined and then launched into HNLF for amplification. Two tunable CW laser sources were employed as parametric pumps and optimized along with the parameters of HNLF, obtaining a flat gain.[28] To maximize the parametric gain, state of polarization of signals is aligned to that of parametric pumps using polarization controller. Finally, selected parametric pump powers and the corresponding wavelengths, along with HNLF parameters are summarized in Table 2.

4 Results and Discussion

The gain spectrum of EYDWA–FOPA hybrid amplifier over the effective wavelength range of 1500 to 1600 nm is shown in Fig. 2, using the parameters listed in Tables 1 and 2. It can be seen that, higher gain (>40 dB) is achieved with better gain flatness in C-band. Also, the gain is higher in C-band, when compared with the amplifier proposed by Yeh et al.[29] The amplifier proposed in this paper is implemented for 100×40 Gb/s DWDM system at reduced channel spacing of 0.2 nm. As observed from Fig. 2, higher gain and lower gain variations are obtained in the upper C-band, so the proposed amplifier is considered for a DWDM wavelength range of 1542 to 1562 nm. Its performance is evaluated in terms of gain and NF at input power of −10-dBm per channel. Variations in gain are also observed at different input powers, FOPA parametric pump powers and HNLF nonlinear coefficients.

The gain and NF spectra of the proposed hybrid EYDWA–FOPA as a function of channel wavelengths,

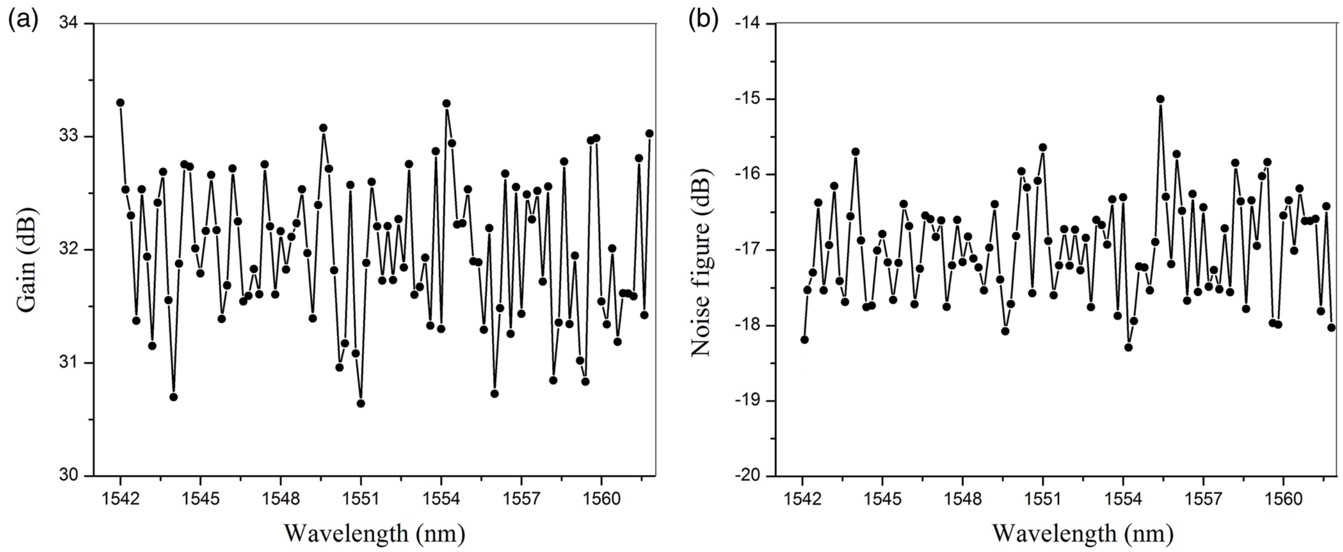

Fig. 3 (a) Gain and (b) NF spectra of proposed amplifier for 100×40 Gb/s DWDM system.

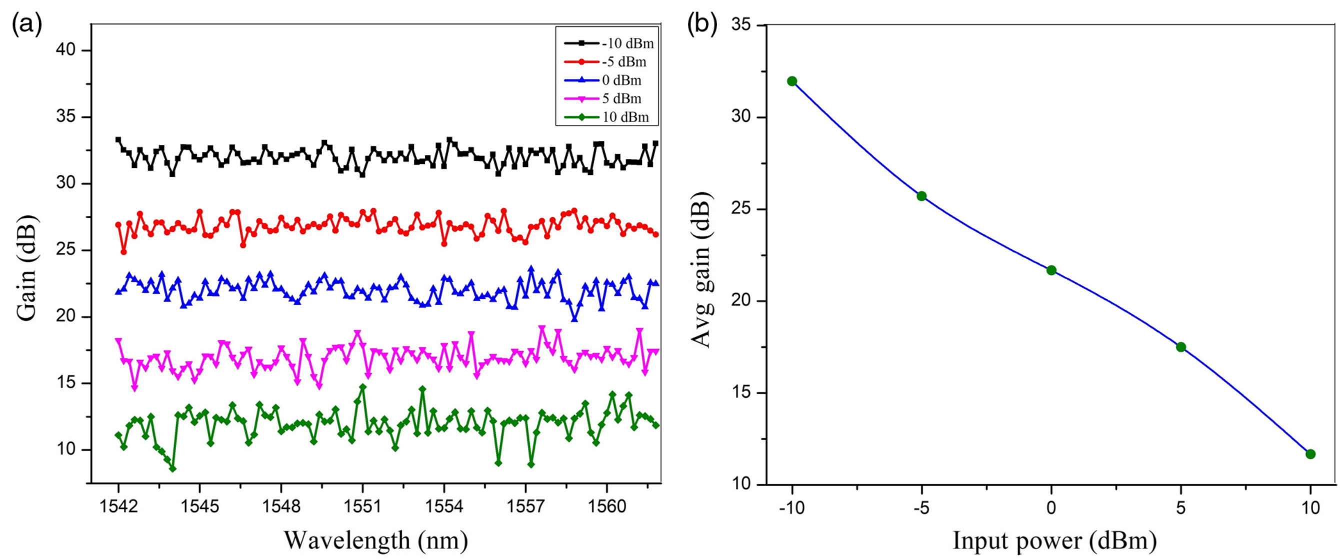

Fig. 4 (a) Gain spectra of proposed hybrid optical amplifier at different per channel input powers and (b) average gain versus input power.

with input power of −10 dBm per channel, are shown in Figs. 3(a) and 3(b), respectively. Nonuniform variations in gain and NF are due to the nonlinearities and ASE noise produced by each amplifier.[19] A gain of >30.6 dB is obtained at each wavelength with a peak value at 1542 nm. Gain ripple of 2.67 dB over the whole effective bandwidth of 20 nm is achieved. The maximum gain for EYDWA is obtained at 1543.6 nm and then it decreases at higher wavelengths. On the other hand, high FOPA gain is achieved at these higher wavelengths, by appropriate tuning of parametric pump wavelengths and powers along with the parameters of HNLF. This results in overall better gain flatness for the hybrid amplifier. Also, significantly low NF values are obtained, as can be seen in Fig. 3(b). The proposed amplifier provides improvement in terms of gain and NF over the amplifier suggested by Singh and Kaler.[30]

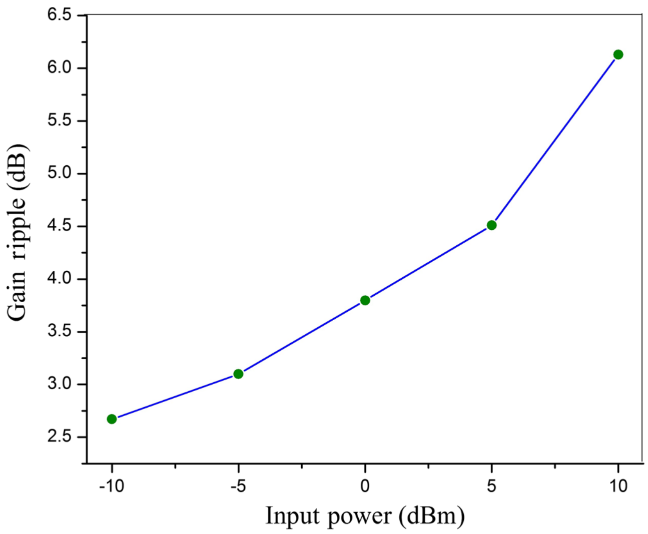

Fig. 5 Gain ripple variations with input power.

The gain of proposed amplifier is also evaluated at different input powers per channel and the resulting profiles for few of them are shown in Fig. 4(a). It can be seen that the maximum gain is achieved at −10-dBm optimum input power. Figure 4(b) shows the decrease in overall gain with an increase in the input power, which is expected due to increased fiber nonlinearities at higher input powers. For convenience, gain ripple values are also calculated over the same input power range. Results, in Fig. 5, show that minimum ripple is observed at −10 dBm. In fact, low gain and large gain variations at higher input powers degrade the system performance due to increased fiber nonlinearities and amplifier saturation effects.

The parametric pump wavelengths and the corresponding powers for FOPA must be carefully selected along with the parameters of HNLF for better gain flatness. In this proposed model, parametric pump wavelengths are closely spaced and symmetrically distributed around zero dispersion wavelength (ZDWL) of HNLF to obtain a flat gain.[31,32] On the other hand, parametric pump powers are varied over a range of values and the gain of proposed amplifier is investigated. The resulting gain spectra of hybrid amplifier for different combinations of the parametric pump powers (P_1 and P_2) are shown in Fig. 6(a). These pump powers (P_1 and P_2) correspond to 1540.9- and 1563.1-nm wavelengths, respectively, and the other FOPA parameters remain same as given in Table 2. Gain ripple values for the gain profiles shown in Fig. 6(a) are also calculated and shown in Fig. 6(b). It can be seen that low gain is achieved with high ripple value when the power of both pumps is 0.5 W each. When both the pumps are being operated at or in the vicinity of 1 W then almost similar gain is achieved. However, minimum ripple value for the proposed amplifier is obtained at $P_1 = 0.8$ W and $P_2 = 1.2$ W. Therefore, these are the finally selected parametric pump powers used in our proposed hybrid configuration.

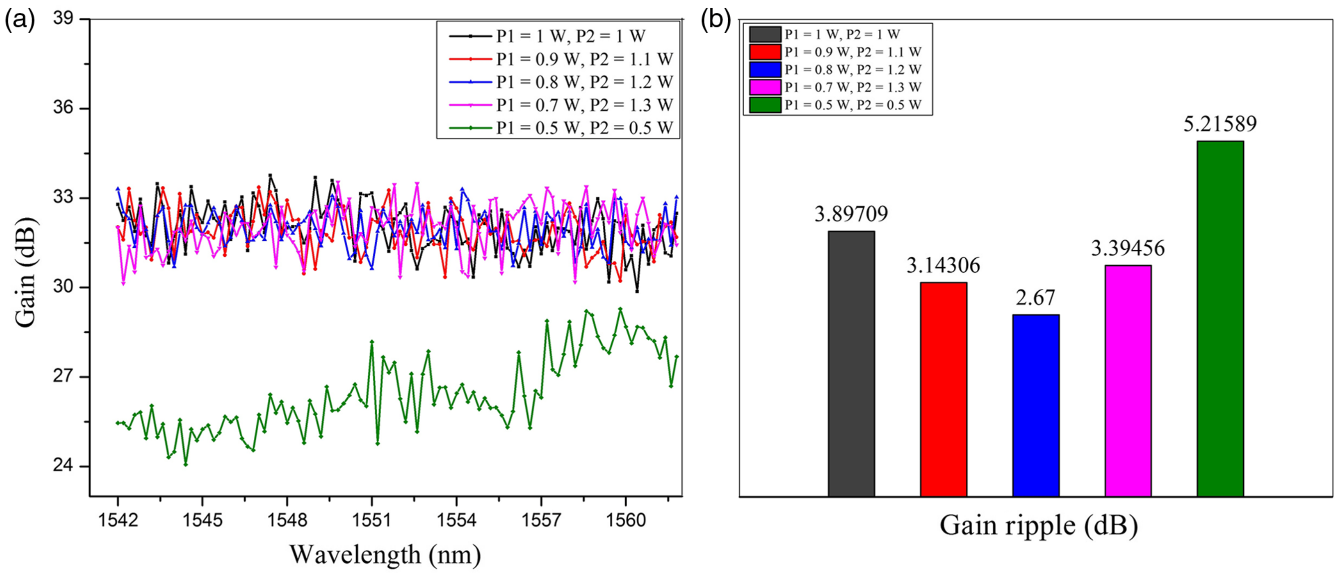

Fig. 6 (a) Gain spectra and (b) gain ripple of proposed amplifier at different FOPA parametric pump powers.

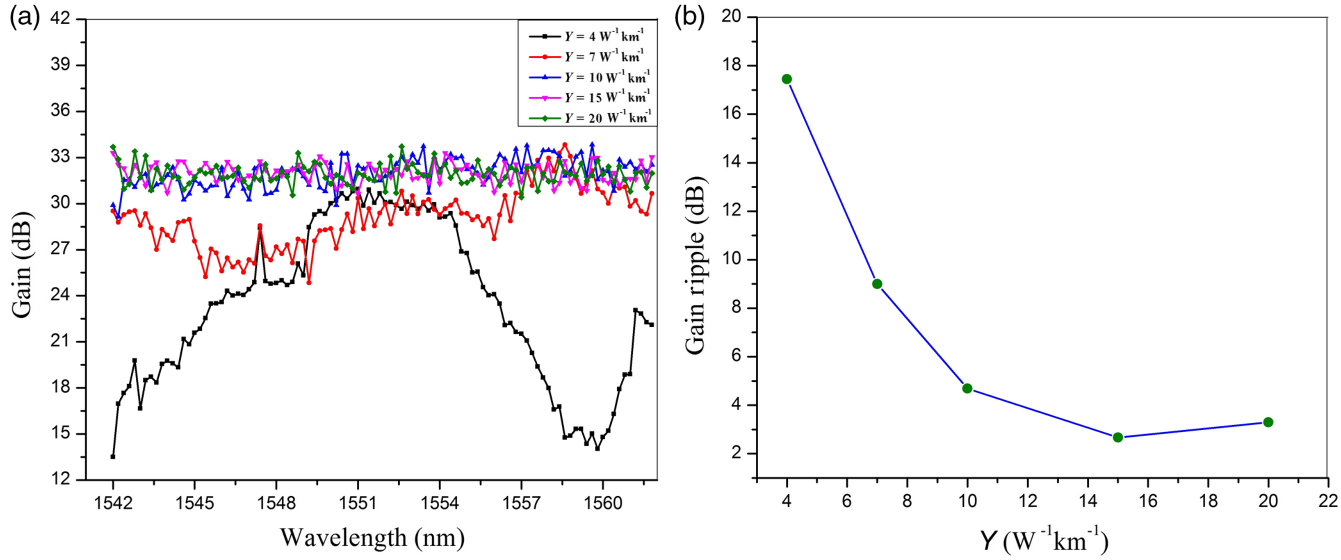

Fig. 7 (a) Gain spectra and (b) gain ripple of proposed amplifier at different HNLF nonlinear coefficients.

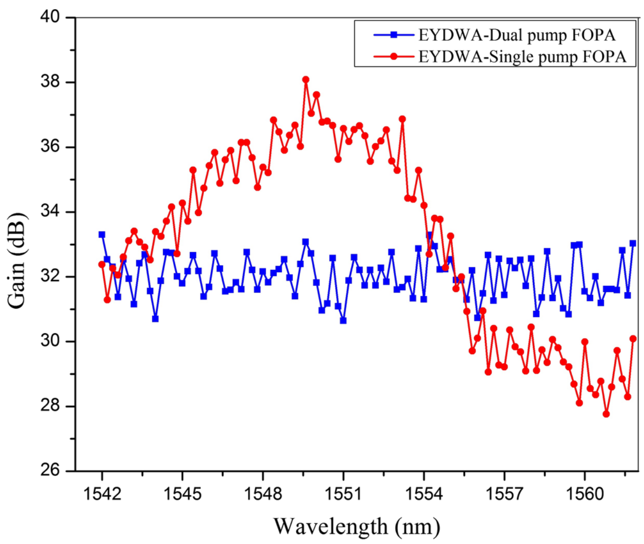

Fig. 8 Gain comparison of EYDWA–dual pump FOPA versus EYDWA–single pump FOPA.

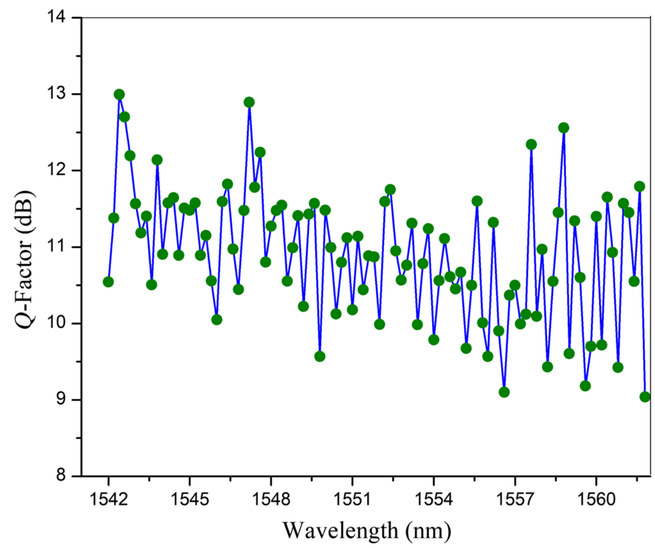

Fig. 9 *Q*-factor as a function of channel wavelengths.

HNLF nonlinear coefficient (γ) is another important parameter affecting the gain and gain flatness of proposed amplifier. The gain is evaluated with variations of γ over a range of 4 to 20 $\mathrm{W^{-1}\,km^{-1}}$ while keeping the other parameters same at input power of -10 dBm. The resulting gain spectra of the proposed amplifier at different nonlinear coefficients and the gain ripple variations are shown in Fig. 7. At $\gamma = 4\ \mathrm{W^{-1}\,km^{-1}}$, low gain is observed with large ripple value. However, improved gain flatness is achieved with an increase in the γ. The ripple value is found to be 2.67 dB at 15 $\mathrm{W^{-1}\,km^{-1}}$, as compared with 17.44 dB at 4 $\mathrm{W^{-1}\,km^{-1}}$. Beyond this value of γ, the ripple again increases slightly, whereas no noticeable change in gain is observed beyond 10 $\mathrm{W^{-1}\,km^{-1}}$. As ripple is found to be minimum at $\gamma = 15.029\ \mathrm{W^{-1}\,km^{-1}}$, so this value is used in the simulation of proposed amplifier.

The parametric amplifier used in this proposed configuration is dual pump, as these are proved to give flat gain.[33,34] A comparison of this dual pump scheme is also performed with EYDWA–single pump FOPA configuration. In case of EYDWA–single pump FOPA, a single parametric pump operating at 1549.1-nm wavelength and having power of 2 W is employed. Results shown in Fig. 8 show better gain flatness in case of dual pump configuration. Gain ripple of 2.67 dB in the proposed configuration as compared with 10.32 dB for EYDWA–single pump FOPA configuration is also an obvious advantage.

The *Q*-factor and BER performance of the system are directly affected by the induced cross talk. The cross talk effects arise because of the nonlinearities produced by optical amplifiers.[35] Figures 9 and 10, respectively, show the *Q*-factor and BER of received electrical signals for the proposed amplifier. Improved values of *Q*-factor (>9 dB) and

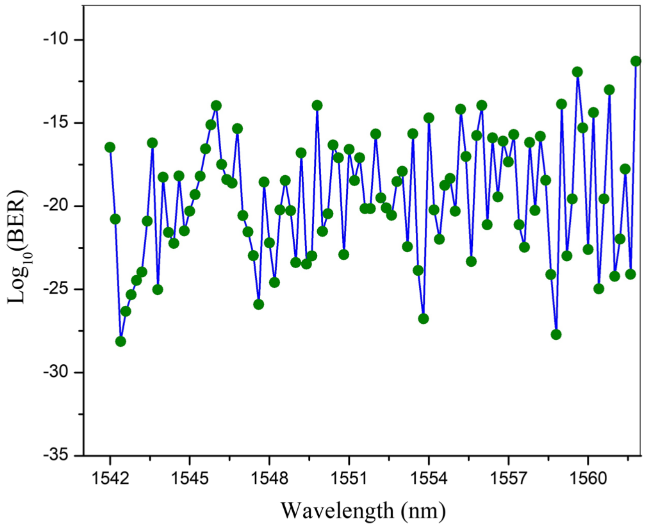

Fig. 10 BER as a function of channel wavelengths.

BER ($<10^{-11}$) are achieved at each wavelength. The variations in Q-factor and BER result because of the nonlinearities induced by each amplifier and interchannel cross talk at small channel spacing and high-input powers.

5 Conclusion

A hybrid optical amplifier, using hybrid EYDWA–FOPA configuration, is proposed and investigated for 100×40 Gb/s DWDM system at channel spacing of 0.2 nm. Optimization processes have been applied to select optimized parameters, resulting in a flat gain of >30.6 dB with a gain flatness of 2.67 dB. No costly gain flattening filter is used. The fall in gain and increase in ripple value is observed with an increase in the per channel input power beyond −10 dBm. Variations in gain are also observed at different FOPA parametric pump powers and HNLF nonlinear coefficients. Gain ripple increases to 10.32 dB (a much higher value as compared with that of the proposed amplifier) for EYDWA–single pump FOPA configuration. The achieved high and flat gain confirms the feasibility of proposed amplifier for broadband long-haul DWDM applications.

References

1. B. Mukherjee, *Optical WDM Networks*, Springer Science & Business Media, New York (2006).
2. H. Suzuki, M. Fujiwara, and K. Iwatsuki, "Application of super-DWDM technologies to terrestrial terabit transmission systems," *J. Lightwave Technol.* **24**(5), 1998–2005 (2006).
3. R. J. Essiambre et al., "Capacity limits of optical fiber networks," *J. Lightwave Technol.* **28**(4), 662–701 (2010).
4. S. Singh, R. Randhawa, and R. S. Kaler, *Handbook on Optical Amplifiers*, Lambert Academic Publishing, Saarbrucken, Germany (2015).
5. S. M. Bilal, M. Zafrullah, and M. K. Islam, "Gain flattening of DWDM channels for the entire C & L bands," *J. Opt. Technol.* **79**(9), 557–560 (2012).
6. S. Singh and R. S. Kaler, "Review on recent developments in hybrid optical amplifier for dense wavelength division multiplexed system," *Opt. Eng.* **54**(10), 100901 (2015).
7. J. H. Lee et al., "A detailed experimental study on single-pump Raman/EDFA hybrid amplifiers: static, dynamic, and system performance comparison," *J. Lightwave Technol.* **23**(11), 3484–3493 (2005).
8. S. M. Bilal, M. Zafrullah, and M. K. Islam, "Achieving gain flattening with enhanced bandwidth for long haul WDM systems," *J. Opt. Technol.* **79**(2), 80–83 (2012).
9. F. Di Pasquale and M. Federighi, "Improved gain characteristics in high-concentration Er^{3+}/Yb^{3+} codoped glass waveguide amplifiers," *IEEE J. Quantum Electron.* **30**(9), 2127–2131 (1994).
10. F. Ondracek et al., "Er–Yb waveguide amplifiers in novel silicate glasses," *IEEE J. Quantum Electron.* **44**(6), 536–541 (2008).
11. C. H. Yeh et al., "Gain-clamping erbium-doped waveguide amplifier module using optical feedback technique," *Opt. Commun.* **246**(3), 73–77 (2005).
12. F. Di Pasquale, S. Faralli, and V. Toccafondo, "$Er^{3+} - Yb^{3+}$ codoped silica waveguide amplifiers longitudinally pumped by broad-area lasers," *IEEE Photonics Technol. Lett.* **19**(24), 1967–1969 (2007).
13. J. Hansryd et al., "Fiber-based optical parametric amplifiers and their applications," *IEEE J. Sel. Topics Quantum Electron.* **8**(3), 506–520 (2002).
14. M. E. Marhic, *Fiber Optical Parametric Amplifiers, Oscillators and Related Devices*, Cambridge University Press, New York (2008).
15. P. Kylemark, "Statistics of wavelength division multiplexed channels in fiber-optical parametric amplification," *J. Lightwave Technol.* **26**(6), 654–662 (2008).
16. B. P. Kuo, P. C. Chui, and K Y. Wong, "A comprehensive study on crosstalk suppression techniques in fiber optical parametric amplifier by modulation format," *IEEE J. Sel. Topics Quantum Electron.* **14**(3), 659–665 (2008).
17. M. Jazayerifar et al., "Performance evaluation of DWDM communication systems with fiber optical parametric amplifiers," *J. Lightwave Technol.* **31**(9), 1454–1461 (2013).
18. S. Z. M. Hasan et al., "Economic and system impact of hybrid Raman–EDFA amplification in a 40×40 Gps optical transmission network with DPSK modulation," *Opt. Fiber Technol.* **19**(1), 10–15 (2013).
19. S. Singh and R. S. Kaler, "Novel optical flat-gain hybrid amplifier for dense wavelength division multiplexed system," *IEEE Photonics Technol. Lett.* **26**(2), 173–176 (2014).
20. M. F. C. Stephens et al., "Improved WDM performance of a fiber optical parametric amplifier using Raman-assisted pumping," *Opt. Express* **23**(2) 902–911 (2015).
21. J. G. Liang et al., "Gain and noise figure of a double-pass waveguide amplifier based on Er/Yb-doped phosphate glass," *Chin. Phys. Lett.* **22**(11), 2862–2864 (2005).
22. Y. H. Wang et al., "Formulized analytical technique for gain characteristics of phosphate glass Er^{3+}/Yb^{3+} co-doped waveguide amplifiers," *Opt. Appl.* **38**(2), 329–339 (2008).
23. E. Rotich and D. Waswa, "Factors affecting dual pump fiber optical parametric amplification gain," in *Sustainable Research and Innovation Proc.*, Vol. 3 (2011).
24. M. N. Islam, *Raman Amplifiers for Telecommunications-1 Physical Principles*, Springer, New York (2004).
25. J. Bromage, "Raman amplification for fiber communications systems," *J. Lightwave Technol.* **22**(1), 79–93 (2004).
26. G. P. Agrawal, *Fiber-Optic Communication Systems*, John Wiley and Sons, New York (2002).
27. R. Stolen and J. Bjorkholm, "Parametric amplification and frequency conversion in optical fibers," *IEEE J. Quantum Electron.* **18**(7), 1062–1072 (1982).
28. D. E. Goldberg, *Genetic Algorithms in Search Optimization and Machine Learning*, Addison-Wesley, New York (1989).
29. C. H. Yeh, M. C. Lin, and S. Chi, "Gain flattened erbium-doped amplifier with 34 nm flat bandwidth," *Electron. Lett.* **42**(19), 1086–1088 (2006).
30. S. Singh and R. S. Kaler, "Performance optimization of EDFA-Raman hybrid optical amplifier using genetic algorithm," *Opt. Laser Technol.* **68**, 89–95 (2015).
31. M. A. Ummy et al., "Extending the gain bandwidth of combined Raman-parametric fiber amplifiers using highly nonlinear fiber," *J. Lightwave Technol.* **27**(5), 583–589 (2009).
32. T. Zhi et al., "Raman-induced asymmetric pump noise transfer in fiber-optical parametric amplifiers," *IEEE Photonics Technol. Lett.* **22**(6), 386–388 (2010).
33. F. Yaman et al., "Impact of pump-phase modulation on dual-pump fiber-optic parametric amplifiers and wavelength converters," *IEEE Photonics Technol. Lett.* **17**(10), 2053–2055 (2005).
34. H. T. Tong et al., "Optical parametric amplification in dual-pumped tellurite hybrid microstructured optical fiber with engineered chromatic dispersion," *J. Phys.: Conf. Ser.* **619**(1), 012052 (2015). IOP Publishing.
35. S. Singh and R. S. Kaler, "Influence of the word length and input power on nonlinear crosstalk induced by hybrid optical amplifiers," *Opt. Fiber Technol.* **19**(5) 428–431 (2013).

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