Optimization of Hybrid Amplifier Parameters for Improved Optical Link Performance

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Research Article

Keywords: Optimization, Hybrid Amplifiers, The Whale Optimization Algorithm, EDFA, Raman Amplifier, Algorithm

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A B S T R A C T

In this manuscript, the gain of the EDFA-Raman hybrid optical amplifier (HOA) is maximized using a popular nature inspired Whale Optimization Algorithm (WOA). The dominating parameters of HOA, length of Raman amplifier and EDFA and its pump powers are optimized to get the maximum possible gain. Further, the performance of WOA is compared by using other metaheuristic techniques such as Real coded Genetic Algorithm, Differential Evolution, Particle Swarm Optimization, to optimize the same model of HOA. WOA proves to be a better optimization technique as it is able to find maximum gain, have a better convergence curve and box plot performance as compared to the other three techniques. Moreover, the gain flatness and noise figure performance of HOA is compared with EDFA and Raman amplifier.

KEYWORDS

Optimization, Hybrid Amplifiers, The Whale Optimization Algorithm, EDFA, Raman Amplifier, Algorithm

1. Introduction

Increasing demand of high data rate and larger bandwidth in optical communication systems become serious issues which can be resolved by using wavelength division multiplexing (WDM) systems [1]. However, using only WDM system does not prove to be sufficient because there are a number of other issues such as attenuation loss and low signal-to-noise ratio (SNR) which degrade the quality of system. The performance characteristics of WDM system largely depend on data rates, modulation schemes used and amplification techniques [2]. Optical amplifiers are key component of WDM system to improve gain and bandwidth [3].

Most widely used optical amplifiers are Erbium doped fiber amplifier (EDFA) and fiber Raman amplifier (FRA). Erbium doped fiber amplifiers (EDFAs) are energy efficient and widely used for C and L band amplification [4]. EDFA amplifiers provide high gain coefficient and cost effectiveness but add amplified spontaneous emission (ASE) noise. Also, gain flatness is limited in EDFA, meaning that additional gain flattening filter must be used to increase the gain bandwidth of amplifier. Raman amplification can provide wide, flat and seamless gain bandwidth over any spectral range with proper choice of pump wavelengths and powers [5]. Raman amplifiers have shown high BER performance but use of Raman amplifiers brings a lot of non- linearities and low gain efficiency [6].

Using hybrid amplifiers (HO) such as a combination of Erbium doped fiber amplifier (EDFA) and Fiber Raman Amplifier (FRA) proves to be an effective solution to provide gain as well as increased bandwidth, capacity, and SNR value of a system. It improves gain flatness and reduces non-linearities of a system. So, cascading both amplifiers is a good solution to these problems. However, for obtaining improved results, optimization of

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main parameters of hybrid model of these amplifiers become indeed important [7].

In [1], system performance is optimized for SOA, EDFA, Raman amplifier and hybrid amplifier with reduced spacing using parameters like Q factor, SNR, gain. M.H.Ali et al [8] has optimized pump power of Raman amplifier using Opti system software. In [9], gain performance is observed for HOA amplifier in C band. However, in [1], [8-9], no global optimization technique has been used to optimize any system performance. [6] optimizes length and pump power of both EDFA and FRA using genetic algorithm. [7] used PSO- a global search technique, to optimize hybrid amplifiers (EDFA/FRA) length of EDFA and pump power of both EDFA and Raman amplifier. In [10], PSO is used to optimize PC-EDFA parameters like N (total erbium ion concentration) and length of EDFA. Algorithms used in [6-7, 10] have many parameters which are user-defined, thus creating difference in results for every user. Also, these algorithms are a little complex to execute. In [11], authors have demonstrated optimization of HOA using algorithms with less computational complexity.

The Whale Optimization Algorithm (WOA) is a new swarm-based meta-heuristic optimization technique which is inspired by the bubble-net hunting strategy of humpback whales [12]. WOA uses non-linear equation to update the positions of particles and that is why the exploration and exploitation ability of WOA is better than other meta-heuristic techniques. Moreover, the steps of exploration and exploitation is done independently, so WOA avoid local optima and achieve faster convergence speed at the same time [13]. These advantages cause WOA to be an appropriate algorithm for solving single objective problems, multi objective problems, different constrained or unconstrained optimization problems for practical applications without structural reformation in the algorithm [14].

The major contribution of this research paper is: 1. Recently developed popular Whale Optimization Algorithm (WOA) has been employed to optimize the parameters of hybrid optical amplifier based on EDFA and Raman amplifier. 2. The optimization task has been carried out with other benchmark algorithms like Differential Evolution (DE), Real coded Genetic Algorithm (RGA) and Particle Swarm Optimization (PSO) and comparative performance evolution has been reported. 3. Gain and noise figure performance of hybrid amplifier is compared with the gain and noise figure achieved by only EDFA and only Raman amplifier.

This paper is ordered as follows: section 2 describes the gain model. Section 3 introduces the optimization techniques used in the paper. Section 4 discusses the results. Section 5 includes the conclusion drawn from the work.

2. Gain Model

Hybrid optical amplifiers work well in C+L band, however optimization of dominating parameters of HOA like EDFA length, FRA length, EDFA pump power, FRA pump power is important to get the maximum gain. The expression for the gain of any system is given by:

$$G = \quad P2/P1 \tag{1}$$

where P1 is the input power given to the system and P2 is the received output power. Fig. 1 represents the schematic diagram of hybrid amplifier used in this paper where EDFA is followed by Raman amplifier. In this hybrid combination, $P_{E\text{-}in}$ is the input signal power given to EDFA, $P_{E\text{-}op}$ is

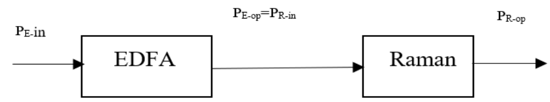

Fig. 1 – Schematic representation of the Hybrid optical amplifier configuration used in this work.

the output power of EDFA which is given to Raman amplifier as its input power $P_{R\text{-}in}$ and $P_{R\text{-}op}$ is the output power of Raman amplifier. So, the expression of gain for hybrid amplifier is given by [6]:

$$\boldsymbol{G = exp\big[L_R exp\{-\sigma_{sa}\Gamma_s N_t L_E + \Gamma_s(\sigma_{sa}+\sigma_{se})N_{2avg}\}g_o - \alpha_s exp\{-\sigma_{sa}\Gamma_s N_t L_E + \Gamma_s(\sigma_{sa}+\sigma_{se})N_{2avg}\}L_R\big]} \tag{2}$$

Where
L_R is the length of Raman amplifier,
L_E is the length of EDFA,
$P_{E\text{-}in}$= P_E= input signal power of EDFA,
$P_{R\text{-}in}$= P_R= input signal power of FRA,
P_{PE}= pump power of EDFA,

$$N_{2avg} = \frac{N_t[\omega_p + \omega_{sa}]L_E}{\left[\omega_p + \left(\frac{1}{\tau_{sp}}\right) + \omega_{sa} + \omega_{se}\right]}$$

$$\omega_{sa} = \frac{\sigma_{sa}P_{E-in}}{a_s h\nu_s}$$

$$\omega_p = \frac{\sigma_{pa}P_{PE}}{a_p h\nu_p}$$

$$\omega_{se} = \frac{\sigma_{se}P_{E-in}}{a_s h\nu_s}$$

$$g_o = \frac{P_{R-in}L_{eff}g_R}{a_p L_R}$$

$$L_{eff} = \frac{[1 - exp(-\alpha_p L_R)]}{\alpha_p}$$

Further details about g_o and N_{2avg} can be viewed in [6].

In eq. (2), length of FRA, length of EDFA, pump power of FRA and pump power of EDFA are kept variable to be optimized, the search space for the length of FRA is 10-45 km, length of EDFA is 10-15 m, pump power of FRA is 100-400 mW and pump power of EDFA is 300-500 mW. The values of rest of parameters are: absorption cross section at signal frequency (σ_{sa}) = $1*10^{-25}m^2$, Emission cross section at signal frequency (σ_{se}) = $2.33*10^{-25}$ m^2, Absorption cross section at pump frequency (σ_{pa}) =$1.86*10^{-25}$ m^2, Emission cross section at pump frequency (σ_{pe}) = $0.42*10^{-25}$ m^2, signal wavelength (λ_s) = 1540 nm, pump wavelength of EDFA (λ_{pE}) = 980 nm, pump wavelength of FRA (λ_{pR}) = 1450 nm, Raman gain coefficient (g_R) =$2.5*10^{-14}$, total Erbium ion concentration (N_t) =$27*10^{23}$ m^{-3}, Fiber loss at signal frequency (α_s) = $36*10^{-5}$ dB/m, Fiber loss at pump frequency (α_p) = $36*10^{-5}$ dB/m, Spontaneous emission lifetime (τ_{sp})= 0.01 sec.

Following assumptions and conditions are considered to reach eq. (2)[6]

- Pump power of Raman amplifier is so large as compared to the signal power that pump depletion can be neglected by settling g_R=0.
- Consider forward pumping only for both amplifiers.
- Fiber losses α and α' are neglected for small fiber length.

3. Optimization Techniques

3.1. The Whale Optimization Algorithm

The Whale Optimization Algorithm (WOA) was introduced by Seyedali Mirjaili and Andrew Lewis in 2016. This meta-heuristic, nature inspired algorithm mimics the social behavior of humpback whales and inspired by bubble-net hunting strategy [15]. Author of this algorithm states that WOA is competitive enough to other state of art meta-heuristic techniques and superior to conventional algorithms. Fig.2 represents the flow chart of WOA. Steps to implement WOA are -

1) Initialize N number of particles for L_R, L_E, P_R, P_E and t number of iterations
2) Calculate the fitness function (G) for all particles using eq. (2)
3) Initialize while loop (t< maximum number of iterations).
4) Initialize for loop for each particle.
5) Update a, A, C, l, p.
6) If p<0.5, either update the position using equation (6) or (7) depending on values of A

$$\vec{D} = \left|\vec{C} * \vec{X}'(t) - X(t)\right| \tag{6}$$

$$\vec{X}(t+1) = \vec{X}_{rand} - \vec{A} \cdot \vec{D} \tag{7}$$

7) If p>0.5, update the position of particles using equation

$$\vec{X}(t+1) = \vec{D}'(t).\ \ e^{bl}.\cos(2\Pi l).\vec{X}'(t) \tag{8}$$

8) Bound the value of particles within decided search space.
9) Update the fitness function for maximum value (as this is maximization problem).
10) End for loop.
11) End while loop.
12) Print maximum fitness function and its corresponding value of L_R, L_E, P_R, P_E.
13) End

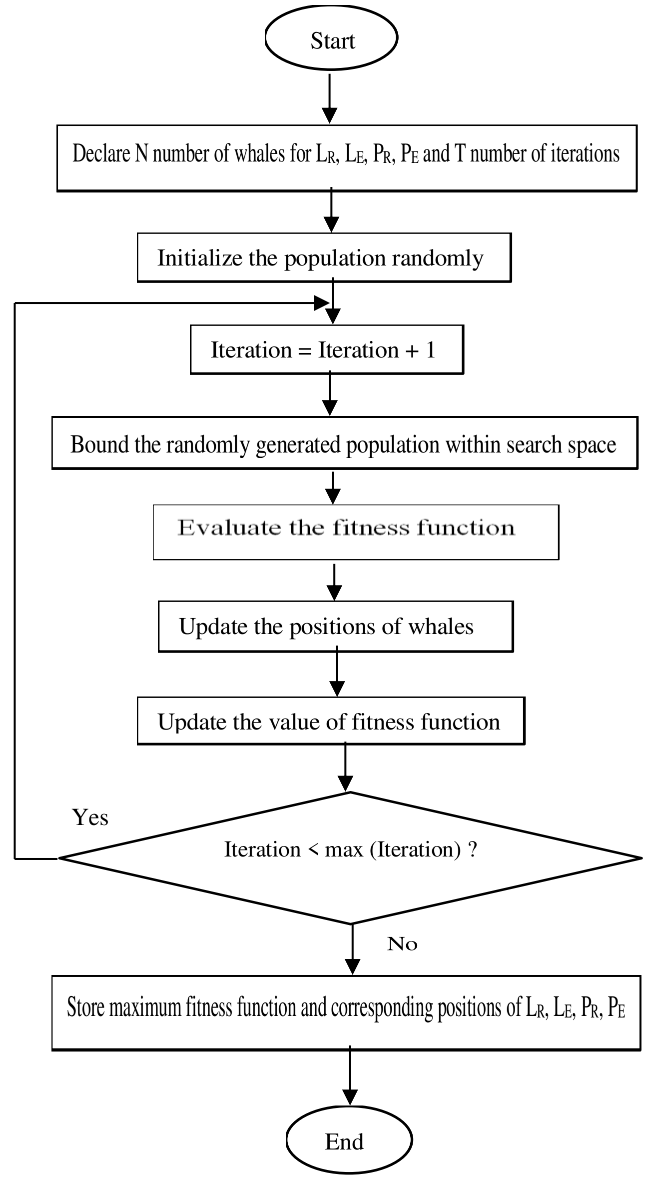

Fig. 2 – Flow chart of The Whale Optimization Algorithm

3.2. Comparative Benchmark Techniques

3.2.1 Real coded Genetic Algorithm

Genetic Algorithm (GA) introduced in 1975, works on the concept of "survival of the fittest". It is a stochastic algorithm based on principle of genetics and evolution [16]. Parameters used while implementing RGA is given in Table 1. Steps to implement GA are as follows: -

1) Generate N number of particles for system variables i.e. L_R, L_E, P_R, P_E within defined search space.
2) Evaluate fitness function using equation (2).
3) Begin loop for fixed number of iterations
   a) Tournament selection: - a competition is organized among randomly generated particles and a vector called parents is generated.
   b) Crossover: - offspring are generated using parent in this step within decided range for each variable.
   c) Mutation: - off springs generated in crossover is mutated by declaring the mutation probability.
4) Generated positions and offspring are arranged, and fitness function is calculated. The maximum N solutions are chosen, and the corresponding values of variables are also stored.
5) Continue till iterations ends.

3.2.2 Differential Evolution

DE was introduced in 1997, it is popular algorithm for population-based search study [17]. DE is less complex algorithm and converges faster as compared to other evolutionary algorithms [16]. Values of parameters used in DE is given in Table 2. Steps to implement DE are as follows: -

1) Generate N number of particles for four variables i.e. L_R, L_E, P_R, P_E within limited search space

2) Begin loop

  a) Generate three random number i.e., r1, r2, r3.

  b) Generate vectors V using equation (2) for all variable

$$V = P_{r1} + F_r * (P_{r2} - P_{r3}) \quad (3)$$

  Where F_r is scaling factor, whose value lies in the range [0,1] and P is position of particle.

  c) Crossover: - generate another vector U

3) Evaluate fitness function (G) using eq. (2), use initial vector and U for variables.

4) Compare evaluated fitness and choose the maximum fitness function and their corresponding value of variables.

5) End loop, when iterations end.

3.2.3 Particle Swarm Optimization

PSO was introduced in 1995, a global optimization approach based on bird flocking and fish schooling [16,18]. Values of parameters of PSO is given in Table 3. Steps to implement PSO are: -

1) Generate N number of position (P) and velocity (V) vector for L_R, L_E, P_R, P_E.

2) Evaluate fitness function for each particle using eq. (2)

3) Start loop for fixed number of iterations

4) Update the value of velocity and position using equation

$$NV^{(t+1)} = w * V^{(t)} + c_1 * rand * \left(L_{best} - P^{(t+1)}\right) + c_2 * rand * \left(G_{best} - P^{(t+1)}\right) \quad (4)$$

$$NP^{(t+1)} = P^{(t+1)} + NV^{(t+1)} \quad (5)$$

where t and t+1 are consecutive iterations, w is inertial weight whose values lies in the range [0,1], c_1 and c_2 are called cognitive parameters and social parameter, respectively. L_{best} is local best and G_{best} is global best value of P.

5) Evaluate the fitness again for updated position vector and compare the fitness functions, call maximum fitness function and its corresponding position vector as local best and best of local best is called global best.

6) End loop, when iteration ends.

7) Print maximum fitness function and global best of all four variables.

Table 1 – Parameters of RGA.

Parameters	**Value**
Number of particles	50
Number of iterations	100
Fitness function	Maximum gain
Cross over probability	0.8
Mutation probability	0.2

Table 2 – Parameters of DE.

Parameters	**Value**
Number of particles	50
Number of iterations	100
Fitness function	Maximum gain
Scaling factor	0.5
Crossover rate	0.5

Table 3 – Parameters of PSO.

Parameters	**Value**
Number of particles	50
Number of iterations	100
Fitness function	Maximum gain
Inertial weight (w)	0.1
Cognitive parameter (c1)	2
Social parameter (c2)	2

Table 4 – Parameters of WOA

Parameters	**Value**
Number of particles	50
Number of iterations	100
Fitness function	Maximum gain
Parameter 'a'	Linearly decreasing from 2 to 0

4. Results and Discussion

Hybrid optical amplifier shown in Fig. 1 is optimized using the four meta-heuristic algorithms which includes evolutionary algorithms like real coded Genetic Algorithm (RGA), Differential Evolution (DE), swarm-based algorithm like Particle Swarm Optimization (PSO), nature inspired

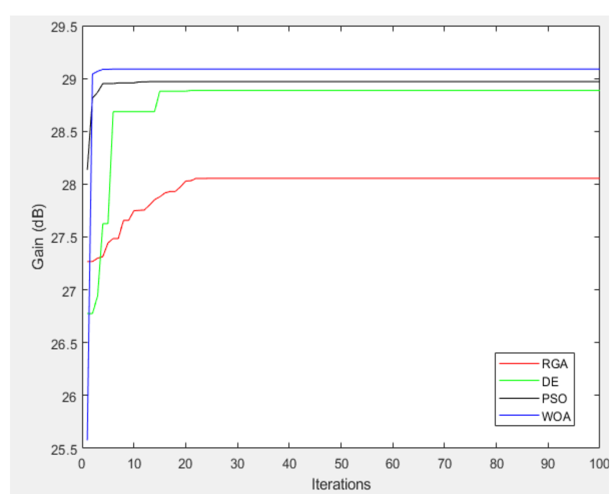

Fig. 3. Convergence Curve of gain obtained by proposed WOA and benchmark algorithms like RGA, DE and PSO

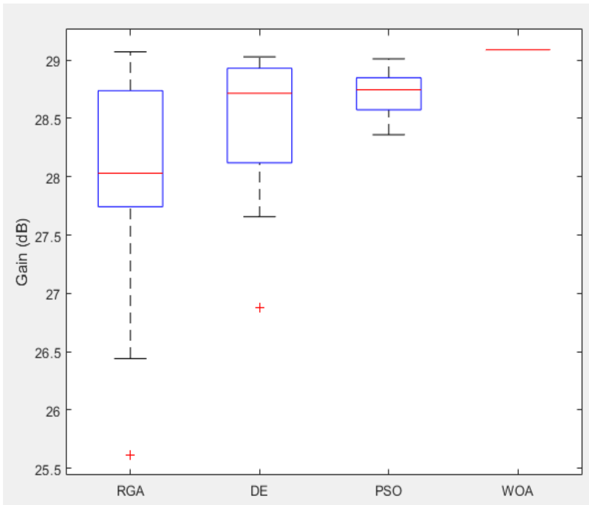

Fig. 4. Box Plot of gain obtained by proposed WOA and comparative RGA, DE, PSO algorithm over 20 independent runs

algorithm like The Whale Optimization Algorithm. Eq. (2) is used as fitness function (G) and the four parameters L_R, L_E, P_R, P_E are optimized to maximize the gain of the amplifier. MATLAB software is used to implement these algorithms.

Fig. 3 shows the convergence curve of all four algorithms, for the comparison of performance of algorithms. The number of particles and number of iterations are kept same i.e. 50 and 100 respectively. WOA gives the maximum gain of 29.09 dB and PSO is able to find the maximum gain of 28.97 dB in given search space, maximum gain achieved by DE is 28.89 dB and maximum gain achieved by RGA is 28.06 dB. WOA converges way faster than rest three algorithms, as WOA takes only 3 iteration to converge, PSO take 11 number of iterations to converge, DE gets converge in 23 iterations and RGA takes 28 iterations. All four algorithms implemented in this paper are metaheuristic in nature. So, it is important to examine the variations in the maximum fitness function when algorithms run multiple times. Fig. 4 is a box plot for all four algorithms, which gives us the maximum, minimum and average value of maximum gain when algorithms are implemented 20 times. From the Fig. 4, it is evident that RGA shows the maximum variation in the results, followed by DE. Results of PSO varies in less range than RGA and DE, and WOA shows almost no variation in results. Table 5 tabulates the maximum gain and optimal values of L_R, L_E, P_R, P_E achieved from all algorithms. The maximum gain is shown by WOA, that is 29.09 dB with length of FRA = 27.64 km, length of EDFA= 12.43 m, pump power of FRA = 400 mW, pump power of EDFA= 418.7 mW. One more parameter to compare the performance of algorithms is computational time. The computational time of WOA is less than other three algorithm, whereas the takes longest time to execute the algorithm.

After optimization, the system performance of the HOA has been evaluated. Fig. 5 shows the schematic diagram of a WDM system in which multiple wavelength input signal is passed through mux, and then this signal is passed through the amplifier block. In the amplifier block, the simulations are carried out for hybrid amplifier as well as by considering individual EDFA and FRA amplifiers in turn, to facilitate comparison.

Table 5 – Optimal value and maximum gain for each algorithm.

Algorithms	Length of FRA (km)	Length of EDFA (m)	Pump power of FRA (mW)	Pump power of EDFA (mW)	Gain (dB)
RGA	28.35	14.09	389	392.7	28.06
DE	27.84	11.7	398	432	28.89
PSO	28.68	13.89	398	361.9	28.97
WOA	**27.64**	**12.43**	**400**	**418.7**	**29.09**

Amplified signal from the output of amplifier is received by receiver through a demultiplexer. Fig. 6. shows the gain profile of only-EDFA, only-Raman amplifier and HOA. To analyze the gain performance of amplifiers (EDFA, FRA, HOA), the rest of the parameters of amplifiers remain same as described in section 2 and gain is obtained at wavelengths in C and L band. Gain profile shows that gain bandwidth of HOA is much wider as compared to only-EDFA and only-Raman amplifier. EDFA shows a good value of gain in C band whereas Raman amplifier shows greater gain than EDFA at almost every wavelength. Fig. 7. shows the noise performance of only-EDFA, only-Raman amplifier and HOA. Noise figure of Raman amplifier is higher than EDFA and HOA, whereas noise figure of HOA is less for entire range of bandwidth.

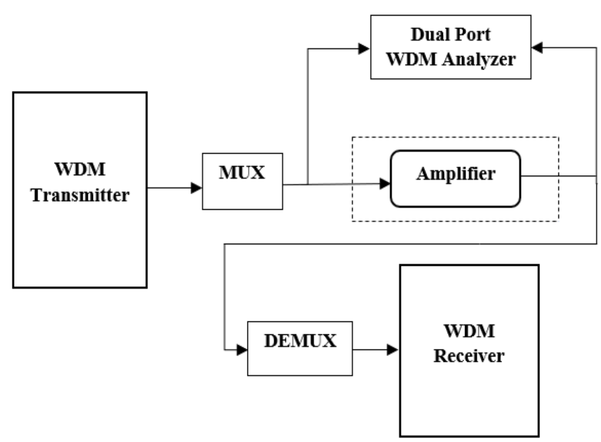

Fig. 5. Block diagram of WDM system

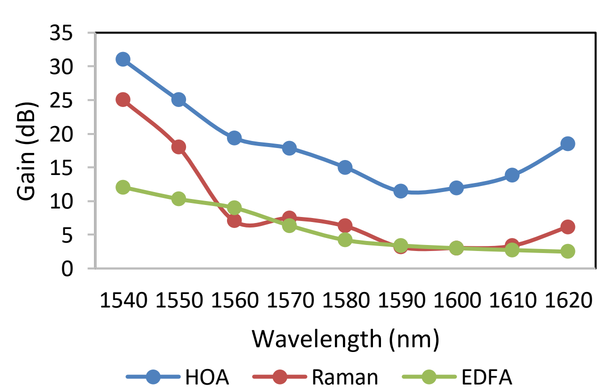

Fig. 6 -Gain profile of HOA, only EDFA and only Raman amplifier

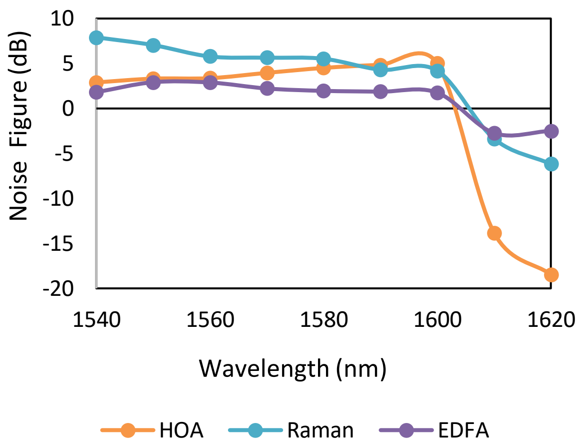

Fig. 7. Noise figure profile of HOA, only EDFA and only Raman amplifier

5. Conclusion

In this paper, optimization of the HOA (a cascaded connection of EDFA and Raman amplifier) have been demonstrated using four different algorithms i.e. Real coded Genetic Algorithm, Differential Evolution, Particle Swarm Optimization and The Whale Optimization Algorithm, and also compared the performance of these algorithms. Four major parameters i.e. FRA length, EDFA length, FRA pump power and EDFA pump power have been optimized, and using the minimum optimal value of these parameters the gain of HOA is maximized. It is found that WOA provides best results among the four algorithms used in this paper as it converges fastest, shows maximum gain of 29.09 dB and it takes minimum elapsed time. This algorithm has minimum user defined parameter which makes it user friendly and shows minimum variation on multiple runs. Also, the gain and noise figure performance of HOA is compared with Raman-only and EDFA-only amplifier and found that the optimized HOA has better gain and noise figure performance.

References

[1] Deepak Malik, Kuldip Pahwa, Amit Wason. Performance Optimization of SOA, EDFA, Raman and hybrid optical amplifiers in WDM network with reduced channel spacing of 50 GHz. Optik 127 (2016) 11131–11137.

[2] H.M. Obaid, H. Shahid. Achieving high gain using Er-Yb codoped waveguide/fiber optical parametric hybrid amplifier for dense wavelength division multiplexed system. Opt. Eng. 57 (2018) 056108.

[3] Hafiz Mohammad Obaid, Hifsa Shahid. Performance evaluation of hybrid optical amplifiers for a 100 ×10 Gbps DWDM system with ultrasmall channel spacing. Optik - International Journal for Light and Electron Optics 200 (2020) 163404.

[4] Md Asif Iqbal et al. Ultra-Wideband Raman Amplifiers for High Capacity Fibre-Optic Transmission Systems. 978-1-7281-8423-4/20/ ©2020 IEEE.

[5] S. Namiki, Y. Emori. Ultrabroad-band Raman amplifiers pumped and gain-equalized by wavelengthdivision-multiplexed high-power laser diodes. IEEE J. Sel. Topics Quantum Electron., vol. 7, no. 1, pp. 3-16, 2001.

[6] Simranjit Singh, R.S. Kaler. Performance optimization of EDFA–Raman hybrid optical amplifier using genetic algorithm. Optics&LaserTechnology68(2015)89–95.

[7] Alireza Mowla, Nosrat Granpayeh. Optimum design of a hybrid erbium-doped fiber amplifier/fiber Raman amplifier using particle swarm optimization. Vol. 48, No. 5 / APPLIED OPTICS/ optical society of America.

[8] M.H.Ali, Alla H.Ali, Sinan M. Abulsatar, Mohammed A. Saleh, A.K.Abass, Thamer Fahad Al-Mashhadani. Pump power optimization for hybrid fiber amplifier utilizing second order stimulated Raman scattering. Optical and Quantum Electronics (2020) 52:274.

[9] Deepak Malik, Geeta Kaushik, Amit Wason. Performance optimization of hybrid amplifier for dense wavelength division multiplexed system. J opt DOI 10.1007/s12596-017-0439-5.

[10] L Mescia, A. Giaquinto, G. Fonaelli, G. Acciani, M. De Sario, F. Prudenzano. Particle swarm optimization for the design and characteristics of silica-based photonic crystal fiber amplifier. Journal of Non-Crystalline Solids 357 (2011) 1851–1855.

[11] Ragini Verma, Vijay Janyani, Satyasai Jagannath Nanda. Design and Optimization of EDFA-Raman Hybrid Optical Amplifier using Grey Wolf Optimizer. International Conference on Communication, Control, and Information Sciences (ICCISc-2021), submitted.

[12] Adel Got, Abdelouahab Moussaoui, Djaafar Zouache. A guided population archive whale optimization algorithm for solving multiobjective optimization problems. Expert Systems with Applications, Volume 141, 2020, 112972, ISSN 0957-4174.

[13] Hardi M. Mohammed, Shahla U. Umar, Tarik A. Rashid, "A Systematic and Meta-Analysis Survey of Whale Optimization Algorithm", Computational Intelligence and Neuroscience, vol. 2019, Article ID 8718571, 25 pages, 2019.

[14] Jhila Nasiri, Farzin Modarres Khiyabani. A whale optimization algorithm (WOA) approach for clustering. Cognent Mathematics & Statistics, Volume 5, 2018 - Issue 1.

[15] Seyedali Mirjalili, Andrew Lewis. The Whale Optimization Algorithm. Advances in Engineering Software 95 (2016) 51–67.

[16] Seng Poh Lim, Habibollah Haron. Performance Comparison of Genetic Algorithm, Differential Evolution and Particle Swarm Optimization Towards Benchmark Functions. 2013 IEEE Conference on Open Systems (ICOS), December 2 - 4, 2013, Sarawak, Malaysia41.

[17] Bilal, Millie Pant, Hira Zaheer, Laura Garcia-Hernandez, Ajith Abraham. Differential Evolution: A review of more than two decades of research. Engineering Applications of Artificial Intelligence 90 (2020) 103479.

[18] James Kennedy, Russell Eberhart. Particle Swarm Optimization. Proceedings of ICNN'95 - International Conference on Neural Networks, Perth, WA, Australia, 1995, 1942-1948 vol.4, 10.1109/ICNN.1995.488968.

Figures

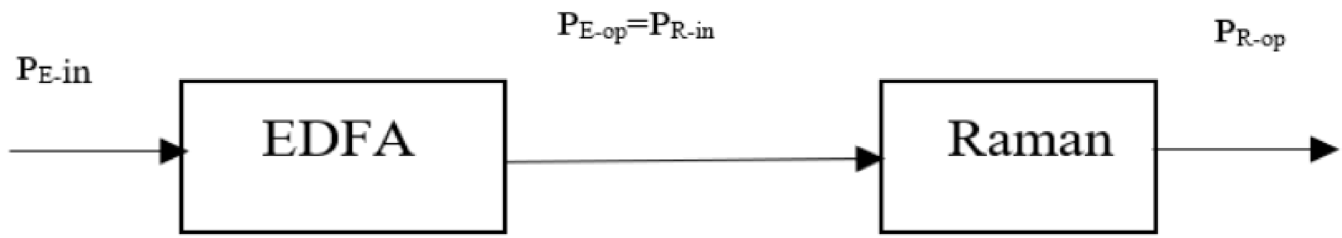

Figure 1

Schematic representation of the Hybrid optical amplifier configuration used in this work.

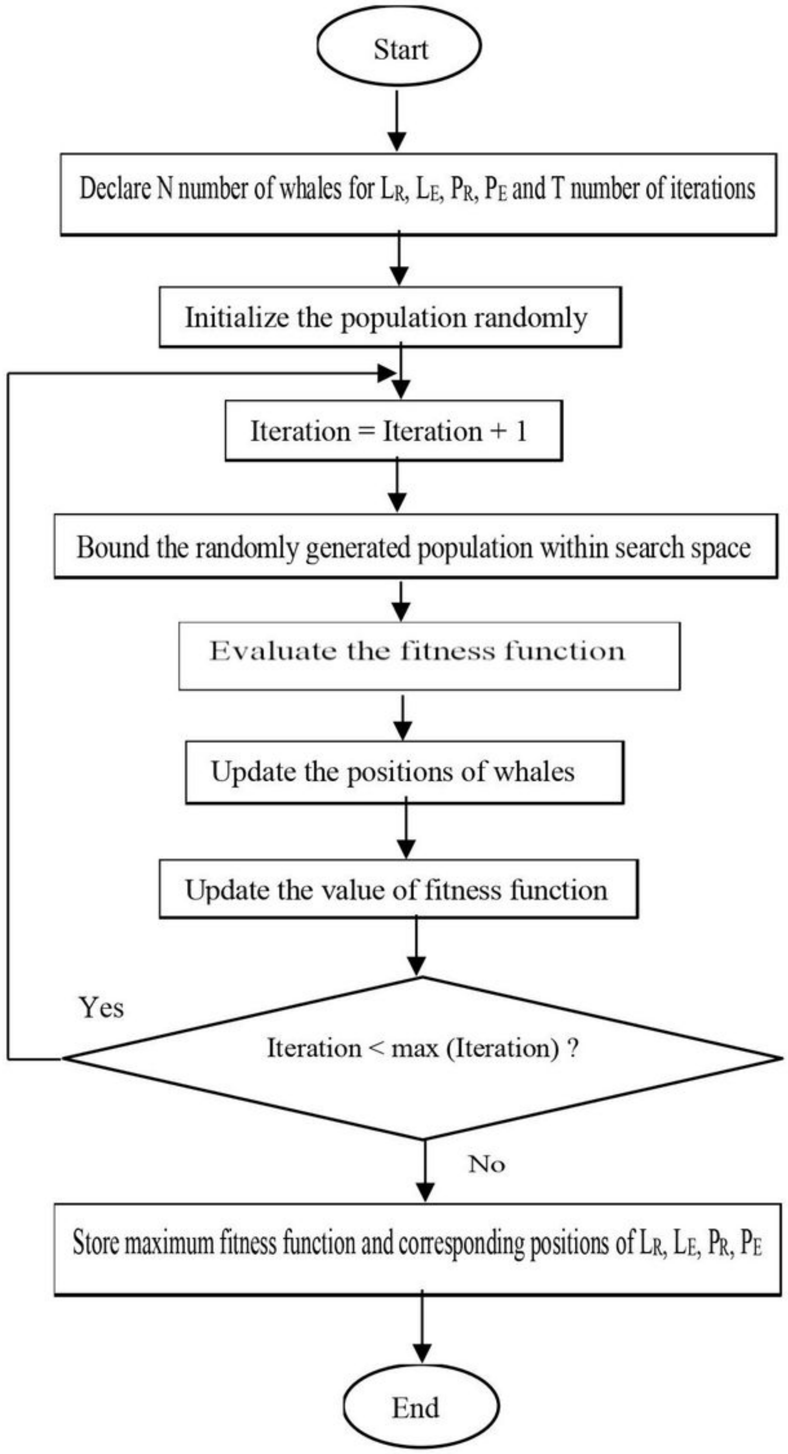

Figure 2

Flow chart of The Whale Optimization Algorithm

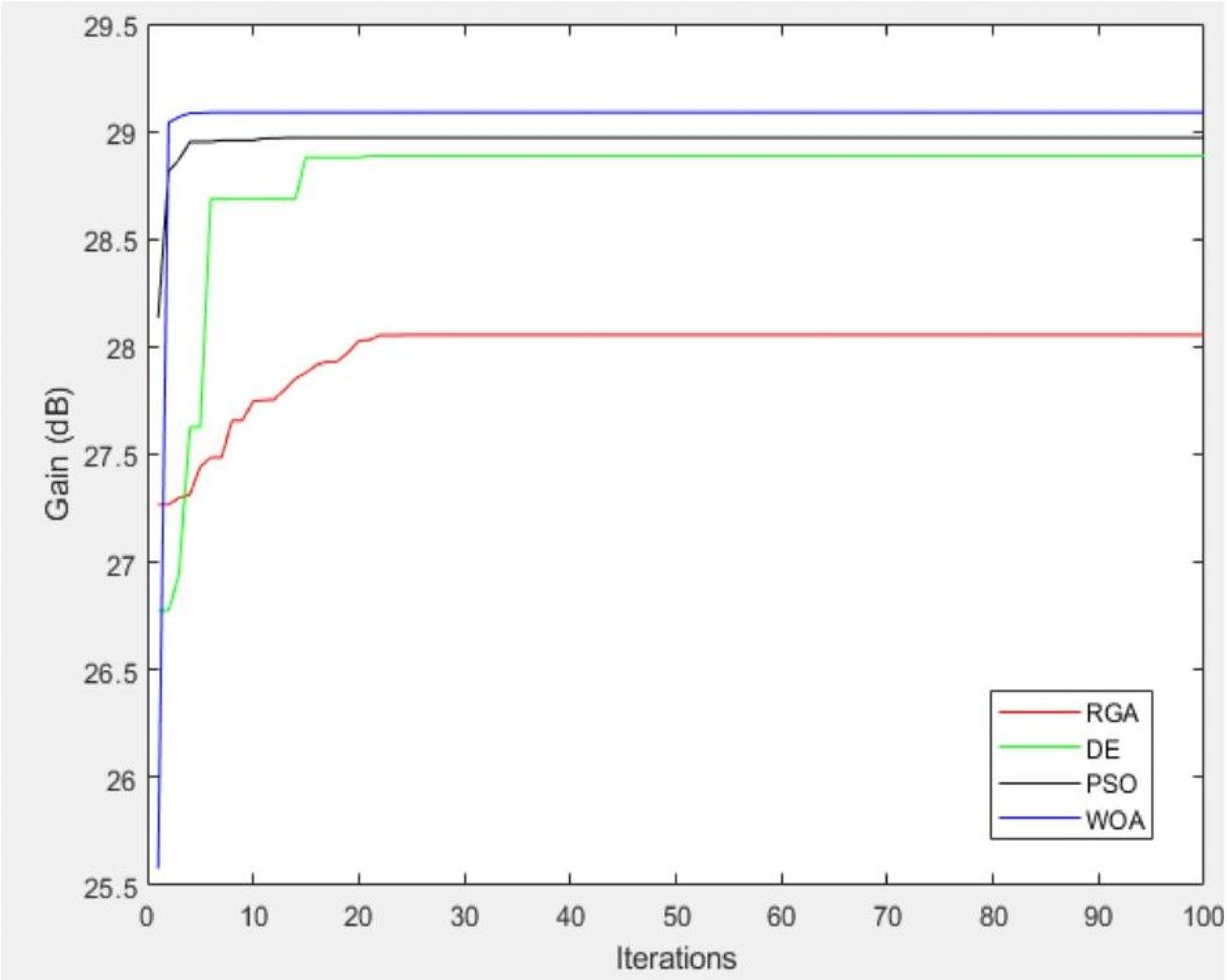

Figure 3

Convergence Curve of gain obtained by proposed WOA and benchmark algorithms like RGA, DE and PSO

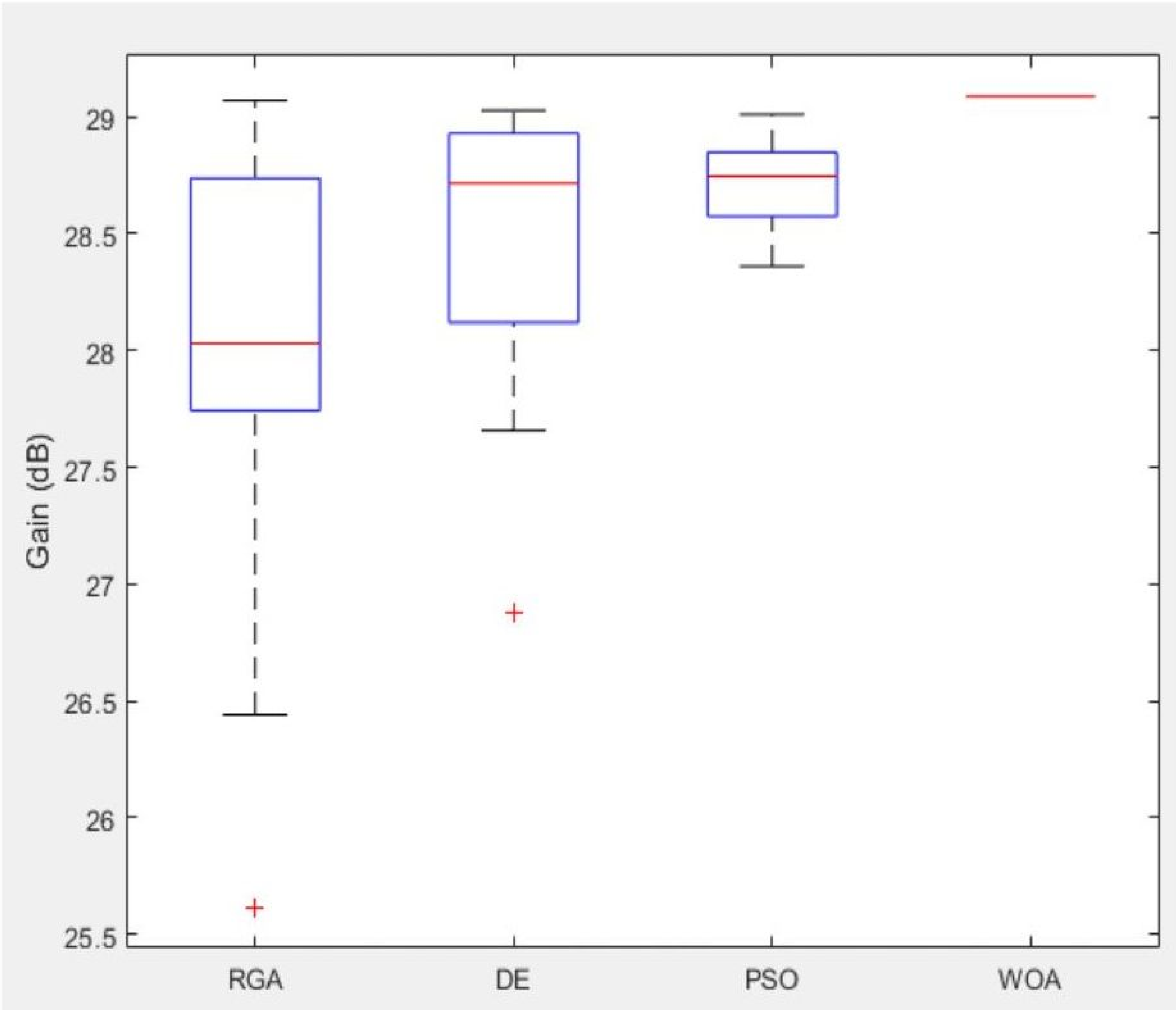

Figure 4

Box Plot of gain obtained by proposed WOA and comparative RGA, DE, PSO algorithm over 20 independent runs

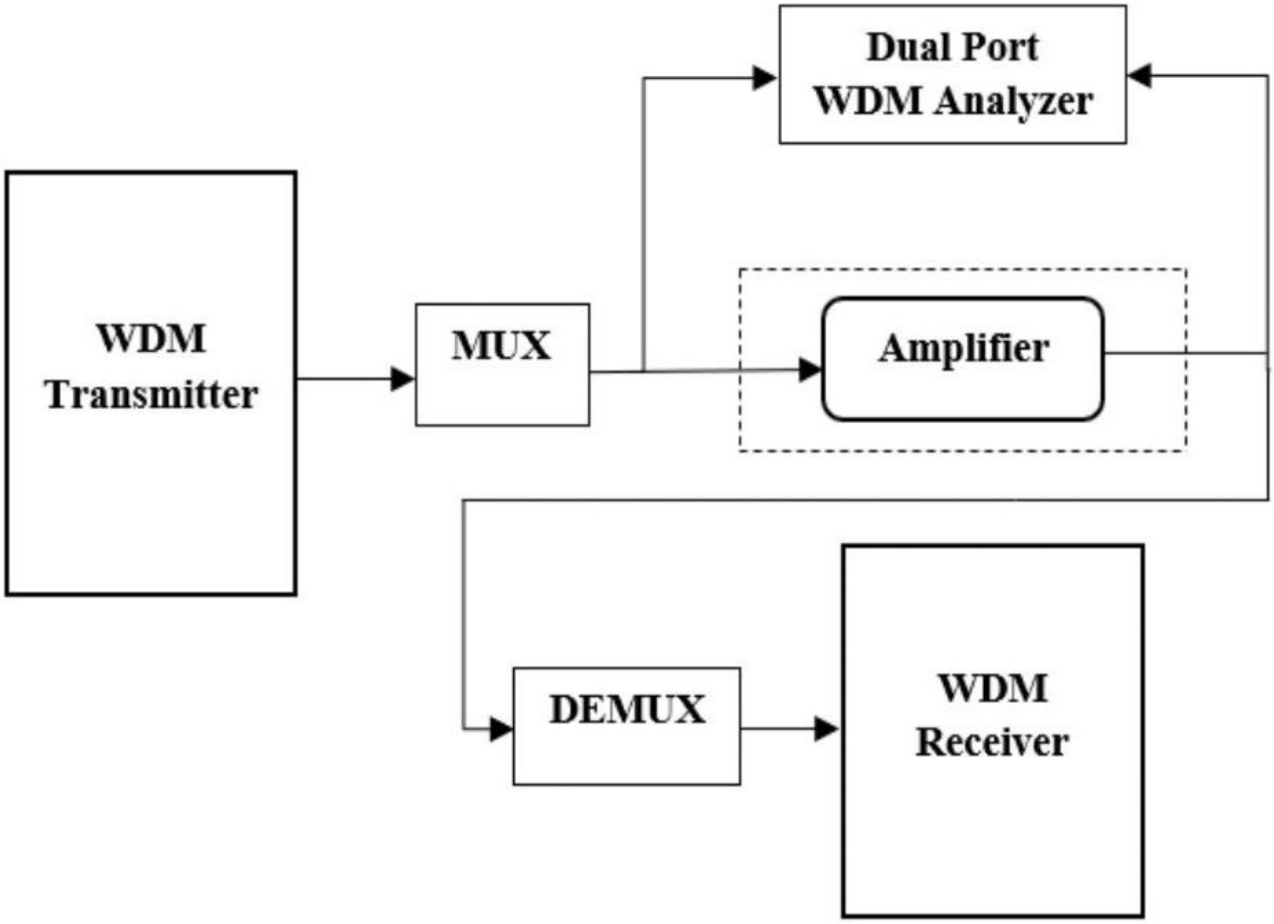

Figure 5

Block diagram of WDM system

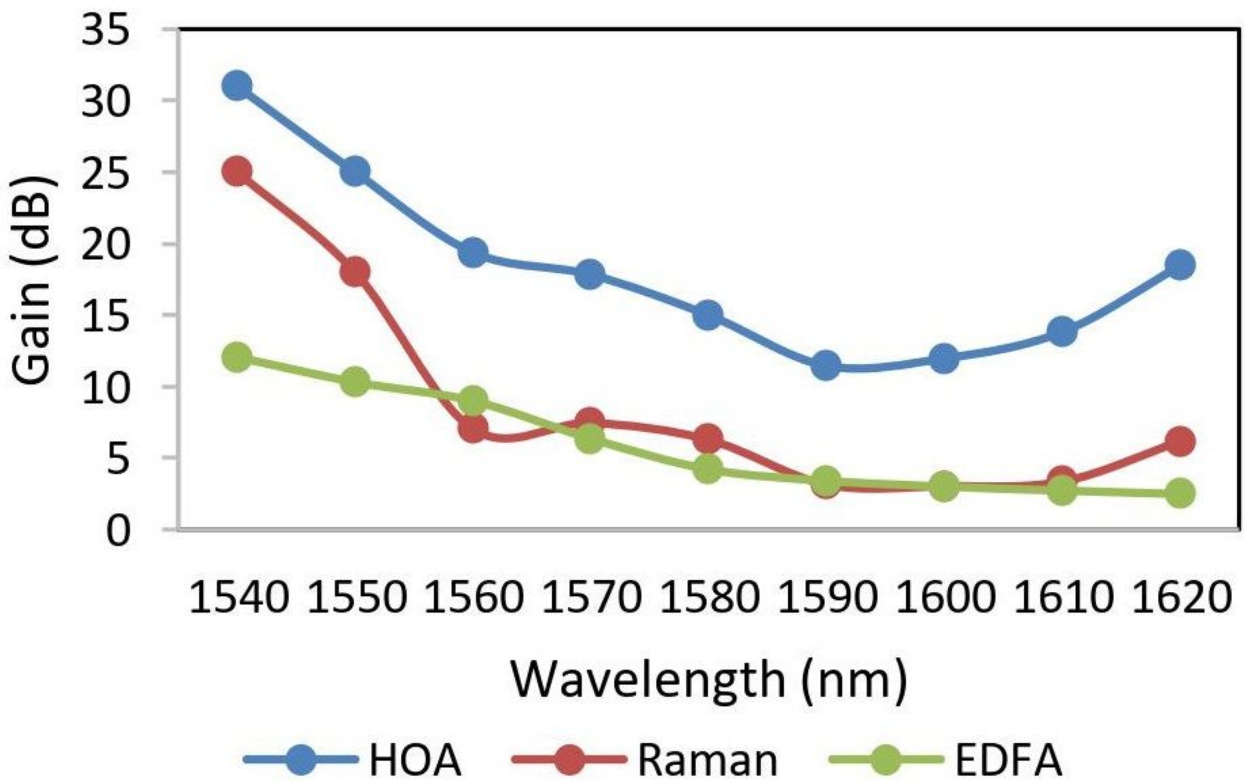

Figure 6

Gain profile of HOA, only EDFA and only Raman amplifier

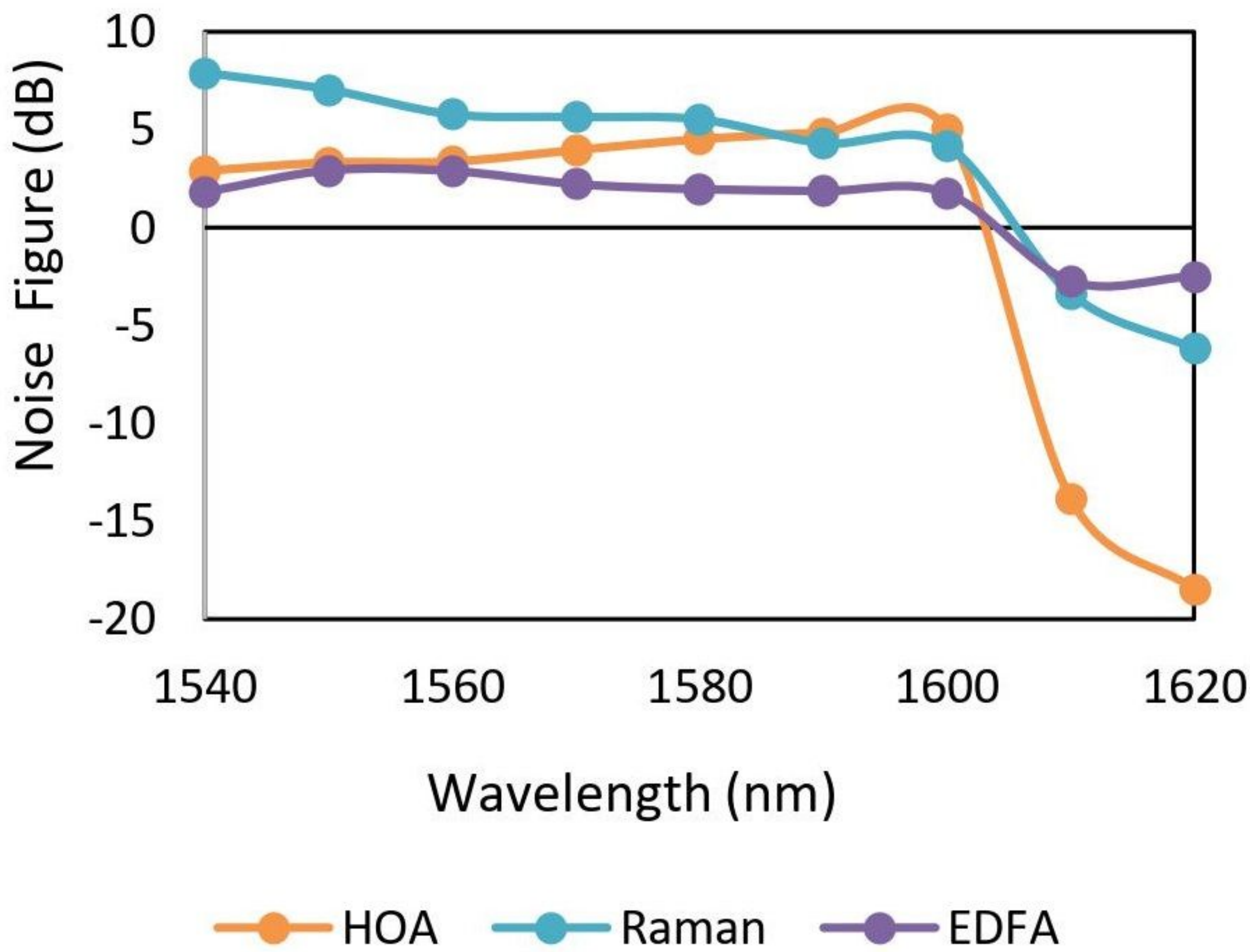

Figure 7

Noise figure profile of HOA, only EDFA and only Raman amplifier