Optimization of hybrid amplifier parameters for improved optical link performance

Ragini Verma · Vijay Janyani · Satyasai Jagannath Nanda

Received: 8 May 2021 / Accepted: 15 July 2021 / Published online: 14 August 2021
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2021

Abstract
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 (Malik et al. 2016). 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 (Obaid and Shahid 2018). Optical amplifiers are key component of WDM system to improve gain and bandwidth (Obaid and Shahid 2020).

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 (Md Asif Iqbal et al. 2020). 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 as shown by (Namiki and Emori 2001). Raman amplifiers have shown high BER performance but use of Raman amplifiers brings a lot of non-linearities and low gain efficiency (Singh and Kaler 2015).

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. The performance of the hybrid amplifier depends on many parameters including emission cross section, absorption cross section, overlapping factor, lengths of EDFA and Raman amplifier, pump power of EDFA and Raman amplifier, doping concentration of EDFA, etc. However, for obtaining improved results, optimization of main parameters of hybrid model of these amplifiers become indeed important such as Mowla and Granpayeh (2009).

In (Malik et al. 2016), system performance is optimized for SOA, EDFA, Raman amplifier and hybrid amplifier with reduced spacing using parameters like Q factor, SNR, gain (Ali et al. 2020) have optimized pump power of Raman amplifier using Opti system software. In (Malik et al. 2017), gain performance is observed for HOA amplifier in C band. However, in Malik et al. (2016, 2017) and Ali et al. (2020), no global optimization technique has been used to optimize any system performance. Singh and Kaler (2015) optimizes length and pump power of both EDFA and FRA using genetic algorithm. Mowla and Granpayeh (2009) 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 Mescia et al. (2011), PSO is used to optimize PC-EDFA parameters like N (total erbium ion concentration) and length of EDFA. Algorithms used in Singh and Kaler (2015), Mowla et al. and Mescia et al. (2011) 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 Verma et al. (2021), 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 (Got et al. 2020). 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 (Mohammed et al. 2019). 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 (Nasiri and Khiyabani 2018).

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: Sect. 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:

\[
G = \frac{P_2}{P_1}
\]

where \(P_1\) is the input power given to the system and \(P_2\) is the received output power. Figure 1 represents the schematic diagram of hybrid amplifier used in this paper where EDFA is followed by Raman amplifier. In this hybrid combination, \(P_{E-in}\) is the input signal power given to EDFA, \(P_{E-op}\) is the output power of EDFA which is given to Raman amplifier as its input power \(P_{R-in}\) and \(P_{R-op}\) is the output power of Raman amplifier. Forward pumping is considered for both the amplifiers, although analysis can be done for backward pumping also in a similar manner. So, the expression of gain for hybrid amplifier is given by (Srimanjit Singh et al. 2015):

\[
G = \exp \left[ L_R \exp \left\{ -\sigma_{sa} \Gamma_s N_s L_E + \Gamma_s \left( \sigma_{sa} + \sigma_{se} \right) N_{2avg} \right\} g_s - \alpha_s \exp \left\{ -\sigma_{sa} \Gamma_s N_s L_E + \Gamma_s \left( \sigma_{sa} + \sigma_{se} \right) N_{2avg} \right\} L_R \right]
\]

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

\[
N_{2avg} = \frac{N_1 \left( \sigma_p + \sigma_{sa} \right) L_E}{\sigma_p \left( \frac{1}{\tau_p} + \sigma_{sa} + \sigma_{se} \right)}
\]

\[
\sigma_{sa} = \frac{\sigma_{sa} P_{E-in}}{a_s h v_s}
\]

\[
\sigma_p = \frac{\sigma_p P_{PE}}{a_p h v_p}
\]

\[
\sigma_{se} = \frac{\sigma_{se} P_{E-in}}{a_s h v_s}
\]

---

**Fig. 1** Schematic representation of the Hybrid optical amplifier configuration used in this work
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 ($\sigma_{sa}$) = $1 \times 10^{-25} \text{m}^2$, Emission cross section at signal frequency ($\sigma_{se}$) = $2.33 \times 10^{-25} \text{m}^2$, Absorption cross section at pump frequency ($\sigma_{pa}$) = $0.42 \times 10^{-25} \text{m}^2$, Emission cross section at pump frequency ($\sigma_{pe}$) = $0.42 \times 10^{-25} \text{m}^2$, signal wavelength ($\lambda_s$) = 1540 nm, pump wavelength of EDFA ($\lambda_{pE}$) = 980 nm, pump wavelength of FRA ($\lambda_{pR}$) = 1450 nm, Raman gain coefficient ($g_R$) = $2.5 \times 10^{-14}$, total Erbium ion concentration ($N_t$) = $27 \times 10^{23} \text{m}^{-3}$, Fiber loss at signal frequency ($\alpha_s$) = $36 \times 10^{-5} \text{dB/m}$, Fiber loss at pump frequency ($\alpha_p$) = $36 \times 10^{-5} \text{dB/m}$, Spontaneous emission lifetime ($\tau_{sp}$) = 0.01 s. Further details about $g_0$ and $N_{2avg}$ can be viewed in Singh and Kaler (2015).

Following assumptions and conditions are considered to reach Eq. (2) (Singh and Kaler 2015).

- Pump power of Raman amplifier is so large as compared to the signal power that pump depletion (the power of pump decrease as the power gets transferred to the signal as both the signal and the pump travels along the length) can be neglected by settling $g_R = 0$.
- Consider forward pumping only for both amplifiers.
- Fiber losses $\alpha$ and $\alpha'$ are neglected for small fiber length.

### 3 Optimization techniques

#### 3.1 The whale optimization algorithm

The Whale Optimization Algorithm (WOA) was introduced by Seyedali Mirjalili 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 as suggested by Mirjalili and Lewis (2016). Author of this algorithm states that WOA is competitive enough to other state of art meta-heuristic techniques and superior to conventional algorithms. Figure 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 ($t < \text{maximum number of iterations}$).
4. Initialize for loop for each particle.
5. Update a, A, C, I, p.
6. If $p < 0.5$, either update the position using Eq. (3) or (4) depending on values of A
If $p > 0.5$, update the position of particles using equation

$$\vec{D} = \left| \vec{C} \ast \vec{X}(t) - X(t) \right|$$

(3)

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

(4)

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

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

(5)

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

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 (Lim and Haron 2013). 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 Eq. (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: offsprings 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 (Bilal et al. 2020). DE is less complex algorithm and converges faster as compared to other

| 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          |
evolutionary algorithms (Lim and Haron 2013). 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., \( r_1, r_2, r_3 \).
   b. Generate vectors \( V \) using Eq. (2) for all variable
      \[ V = P_{r1} + F_r \times \left( P_{r2} - P_{r3} \right) \] (6)
      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 (Lim and Haron 2013; Kennedy and Eberhart 1995). Values of parameters of PSO is given in Table 3. Steps to implement PSO are:

#### 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                |
(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

\[
NV^{(t+1)} = w \ast V(t) + c_1 \ast \text{rand} \ast (L_{\text{best}} - P^{(t+1)}) + c_2 \ast \text{rand} \ast (G_{\text{best}} - P^{(t+1)})
\]

(7)

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. \( L_{\text{best}} \) is local best and \( G_{\text{best}} \) 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.

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 algorithm like The Whale Optimization Algorithm. Equation (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 (Table 4).

Figure 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 (any other value of the number of particles and number of iterations can be used, the values considered here are sufficient enough to run the algorithm of this work). 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.

| Parameters        | Value                     |
|-------------------|---------------------------|
| Number of particles | 50                        |
| Number of iterations | 100                      |
| Fitness function   | Maximum gain              |
| Parameter ‘a’      | Linearly decreasing from 2 to 0 |
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. Figure 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 $L_{\text{R}}, L_{\text{E}}, P_{\text{R}}, P_{\text{E}}$ 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 RGA takes longest time to execute the algorithm.

After optimization, the system performance of the HOA has been evaluated. Figure 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.

Amplified signal from the output of amplifier is received by receiver through a demultiplexer. Figure 6. shows the gain profile of only-EDFA, only-Raman amplifier and HOA. To analyze the advantages of the Hybrid Amplifiers in WDM system, the gain performance of amplifiers (EDFA, FRA, HOA) have been studied. For this purpose, first the EDFA is placed at the amplifier block, then FRA is placed (with only single pump corresponding to 1540 nm wavelength) and then both are placed in cascaded connection at the place of amplifier block. The values of parameters used is same as that used for the optimization purpose (mentioned in Sect. 2). The channel spacing used is 10 nm, it is observed that as channel spacing decreases the gain of the system decreases.
increases, and noise figure decreases. 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 higher gain than EDFA at almost every wavelength. A better gain spectrum can be obtained when multiple pumps corresponding to the complete wavelength range is given to FRA but in this work, the aim is to compare the performance of EDFA, FRA and HOA at 1540 nm only therefore single pump for 1540 nm has been used. The gain obtained by HOA at 1540 nm is slightly higher in the WDM system than the optimized value because of the fact that the input signal given to EDFA (in the cascaded connection of HOA) get affected by many parameters like modulation techniques, channel spacing, wavelength band, etc. Figure 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.

Table 5 Optimal value and maximum gain for each algorithm

| Algorithms | Length | Pump power | Gain (dB) | Elapsed time (msec) | Iteration |
|------------|--------|------------|-----------|---------------------|-----------|
|            | FRA (km) | EDFA (m) | FRA (mW) | EDFA (mW) |         |         |
| RGA        | 28.35   | 14.09     | 389       | 392.7     | 28.06   | 359     | 28      |
| DE         | 27.84   | 11.7      | 398       | 432       | 28.89   | 212     | 23      |
| PSO        | 28.68   | 13.89     | 398       | 361.9     | 28.97   | 152     | 11      |
| WOA        | 27.64   | 12.43     | 400       | 418.7     | 29.09   | 140     | 3       |
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. Use of non-linear weight update equations makes WOA a better search technique and thus it has ability to perform better than rest of the optimization techniques. 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.

Availability of data and material  Yes, papers from where material is consulted have been mentioned in the references.

Code availability  Yes, standard algorithms are taken from papers mentioned in references.

Declarations

Conflict of interest  Not applicable.

Consent to applicable  Yes.

Consent for publication  Yes.

References

Ali, M.H., Ali, A.H., Abulsatar, S.M., Saleh, M.A., Abass, A.K., Al-Mashhadani, T.F.: Pump power optimization for hybrid fiber amplifier utilizing second order stimulated Raman scattering. Opt. Quantum Electron. 52, 274 (2020)

Bilal, Pant, M., Zaheer, H., Garcia-Hernandez, L., Abraham, A.: Differential Evolution: A review of more than two decades of research. Eng. Appl. Artif. Intell. 90, 103479 (2020)

Got, A., Moussaoui, A., Zouache, D.: A guided population archive whale optimization algorithm for solving multiobjective optimization problems. Expert Systems with Applications, Vol. 141, 2020, 112972, ISSN 0957-4174

Kennedy, J., Eberhart, R.: Particle Swarm Optimization. Proceedings of ICNN’95—International Conference on Neural Networks, Perth, WA, Australia, 1995, 1942–1948 Vol. 4, https://doi.org/10.1109/ICNN.1995.488968

Lim, S.P., Haron, H.: 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, Malaysia 41

Malik, D., Pahwa, K., Wason, A.: Performance optimization of SOA, EDFA, Raman and hybrid optical amplifiers in WDM network with reduced channel spacing of 50 GHz. Optik 127, 11131–11137 (2016)
Optimization of hybrid amplifier parameters for improved optical…

Malik, D., Kaushik, G., Wason, A.: Performance optimization of hybrid amplifier for dense wavelength division multiplexed system. J. Opt. (2017). https://doi.org/10.1007/s12596-017-0439-5

Iqbal, M. A., Krzczanowicz, L., Phillips, I. D., Harper, P., Lord, A., Forysiak, W.: Ultra-wideband Raman amplifiers for high capacity fibre-optic transmission systems. 22nd International Conference on Transparent Optical Networks (ICTON). pp. 1–4 (2020). https://doi.org/10.1109/ICTON51198.2020.92033

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

Mirjalili, S., Lewis, A.: The Whale Optimization Algorithm. Adv. Eng. Softw. 95, 51–67 (2016)

Mohammed, H.M., Umar, S.U., Rashid, T.A.: A systematic and meta-analysis survey of whale optimization algorithm. Comput. Intell. Neurosci. Vol. 2019, Article ID 8718571, 25 pages (2019)

Mowla, A., Granpayeh, N.: 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

Namiki, S., Emori, Y.: Ultrabroad-band Raman amplifiers pumped and gain-equalized by wavelength-multiplexed high-power laser diodes. IEEE J. Sel. Top. Quantum Electron. 7(1), 3–16 (2001)

Nasiri, J., Khiyabani, F.M.: A whale optimization algorithm (WOA) approach for clustering. Cognent Math. Stat. 5(1) (2018)

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

Obaid, H.M., Shahid, H.: Performance evaluation of hybrid optical amplifiers for a 100 \times 10 \text{ Gbps DWDM system with ultrasmall channel spacing}. Opt.—Int. J. Light Electron Opt. 200, 163404 (2020)

Singh, S., Kaler, R.S.: Performance optimization of EDFA–Raman hybrid optical amplifier using genetic algorithm. Opt. Laser Technol. 68, 89–95 (2015)

Verma, R., Janyani, V., Nanda, S.J.: Design and Optimization of EDFA-Raman hybrid optical amplifier using grey wolf optimizer. International Conference on Communication, Control, and Information Sciences (ICCISc-2021) 978-1-6654-0295-8/21 (pp. 1–6)

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.