Adaptive Neuro-Fuzzy Based Gain Controller for Erbium-Doped Fiber Amplifiers

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***Abstract*—Erbium-doped fiber amplifiers (EDFA) must have a flat gain profile which is a very important parameter such as wavelength division multiplexing (WDM) and dense WDM (DWDM) applications for long-haul optical communication systems and networks. For this reason, it is crucial to hold a stable signal power per optical channel. For the purpose of overcoming performance decline of optical networks and long-haul optical systems, the gain of the EDFA must be controlled for it to be fixed at a high speed. In this study, due to the signal power attenuation in long-haul fiber optic communication systems and non-equal signal amplification in each channel, an automatic gain controller (AGC) is designed based on the adaptive neuro-fuzzy inference system (ANFIS) for EDFAs. The intelligent gain controller is implemented and the performance of this new electronic control method is demonstrated. The proposed ANFIS-based AGC-EDFA uses the experimental dataset to produce the ANFIS-based sets and the rule base. Laser diode currents are predicted within the accuracy rating over 98 percent with the proposed ANFIS-based system. Upon comparing ANFIS-based AGC-EDFA and experimental results, they were found to be very close and compatible.**

***Index Terms*—fuzzy neural networks, adaptive control, gain control, power control, erbium-doped fiber amplifiers.**

I. INTRODUCTION

Fiber optic communication systems develop rapidly due to a growing demand of subscribers for quality video, IPTV, online chat, e-government applications, etc. WDM and optical amplifiers which are generally EDFAs are the key parameters of these systems. They are widely used in long-haul optical communication systems (LHOCS) to provide high capacity and high-speed transmission [1-4].

The transmission of optical signal channels is a significant factor in all types of fiber optic communication systems. However, the signal power is attenuated in long-haul optical systems and then must be amplified in the fiber-optic amplifier. In addition, signal amplification for each channel out of the EDFAs is non-equal. For this reason, the optical gain control must be performed in EDFAs. In these systems, a flat gain spectrum and add/drop processes of the channels are the other two significant parameters [5-8]. The first parameter is more significant in LHOCSs due to the intrinsic wavelength dependence of gain. In the EDFA series, the variations of the signal power among the WDM/DWDM channels degrade the performance. The second parameter is the number of the channels present in an EDFA which changes due to the network readjustment or channel errors. Therefore, the output signal gain control of EDFAs is a significant subject for WDM/DWDM network systems. To overcome the performance deterioration, it is extremely important to hold a stable signal level per each optical channel [5-8]. Thus, the EDFA gain should be checked so as to be fixed at high-speed variations [9]. Numerous automatic gain control (AGC) configurations are suggested in the literature to obtain the stable signal level at the output of EDFAs and they are classified as electronic, optical or hybrid [9-20]. However, electronic control (EC) methods have stabilizing time such as 1 microsecond lower than all-optical control methods but more sophisticated [10]. In this study, a novel EC-AGC method is recommended with the use of ANFIS by using the data obtained from the previous study [20]. The results obtained in this paper have faster convergence with the inclusion of the automatic tuning of ANFIS parameters.

ANFIS is one of the popular neuro-fuzzy methods that is the hybrid combination of artificial neural networks (ANNs) and is based on Takagi–Sugeno fuzzy inference system (FIS) [21-23]. Likewise, in benchmarking with other artificial learning methods, ANFIS has a superior speed of training, the most powerful learning algorithm, elementary software [24], and it is faster in convergence. The artificial intelligence methods are widely used for estimating, forecasting, classifying, recognition, diagnosing [25-32], and controlling the electronic and optical applications [33-42]. However, the ANFIS-based AGC model for EDFAs is firstly proposed in this work. In addition, the suggested ANFIS software is embedded easily in the electronic card, which is performed in the previous study [20].

The article is structured as follows. In Section 2, the background on ANFIS is given. Section 3 contains ANFIS results obtained for the AGC-EDFA. Finally, Section 4 reports the conclusion.

II. PROPOSED ANFIS MODEL FOR THE AGC-EDFA

There are different combinations of soft computing methods. One of them has the highest appearance that is the integration of fuzzy logic and neuro-computing, so-called neuro-fuzzy systems. ANFIS, which is an adaptive neuro-fuzzy system, is developed for the effective modeling of nonlinear systems/structures. These systems use ANNs theory to define fuzzy sets and fuzzy rules by processing

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data sets [43-48]. The membership functions (MF) are obtained from a data set representing the nonlinear system attitude. ANFIS finds out the properties of the data set. The nonlinear system parameters are arranged by ANFIS with reference to the failure criterion [46- 49].

Fig. 1 shows the structure of an ordinary ANFIS model. This model is five-layered, it has two inputs, two rules, and one output [46].

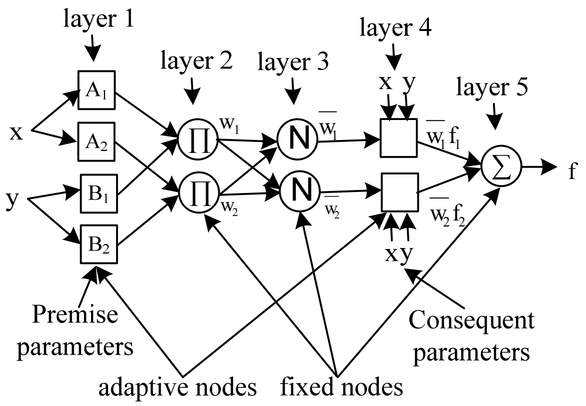

Figure 1. The first order Takagi-Sugeno interference system (Type-3 ANFIS) [40]

In this model, an ordinary rule base with four if–then rules can be expressed as follows:

Rule 1: If x is A_1 and y is B_1 then $f_1 = p_1x + q_1y + r_1$

Rule 2: If x is A_2 and y is B_2 then $f_2 = p_2x + q_2y + r_2$

where x and y are input variables, f_1 and f_2 are output levels, A_1, A_2, B_1 and B_2 are membership functions for inputs, p_{ij}, q_{ij} and r_{ij} (i, j = 1, 2) are sequenced parameters and f is the output parameter of the whole system.

The first layer is also called fuzzification layer, where the input data are fuzzified and neuron values are represented by parameterized MFs. The output of the i-th client in layer l is expressed as O. If the MF is a generalized bell-shaped function, the output can be written as below [46-52]:

$$O_j^1 = \frac{1}{1+(\dfrac{x-c_i}{a_i})^{2N_i}} \tag{1}$$

where, a_i, c_i, N_i are customizable variables. Furthermore, these variables are known as premise parameters. The outputs of the first layer are the MF rates of the premise parameters.

The second layer is also called rule layer where the activation of fuzzy rules is calculated. Each node in layer 2 multiplies the arriving values as:

$$O_j^2 = w_j = \mu_{Aj}(x) \times \mu_{Bj}(y) \tag{2}$$

The third layer is also called normalization layer where all nodes are fixed. The j-th client of the third layer computes the normalized firing strengths as:

$$O_j^3 = \overline{w_j} = \frac{w_j}{w_1 + w_2} \tag{3}$$

The fourth layer is also called defuzzification layer. In this layer, the sequenced part is acquired through the linear regression analysis or multiplication between normalized activation level and the output of the concerned rule. Node j in the fourth layer computes the contribution of the j-th rule against the system output, and can be found with the following expression:

$$O_j^4 = \overline{w_j} f_j = \overline{w_j}(p_j x + q_j y + r_j) \tag{4}$$

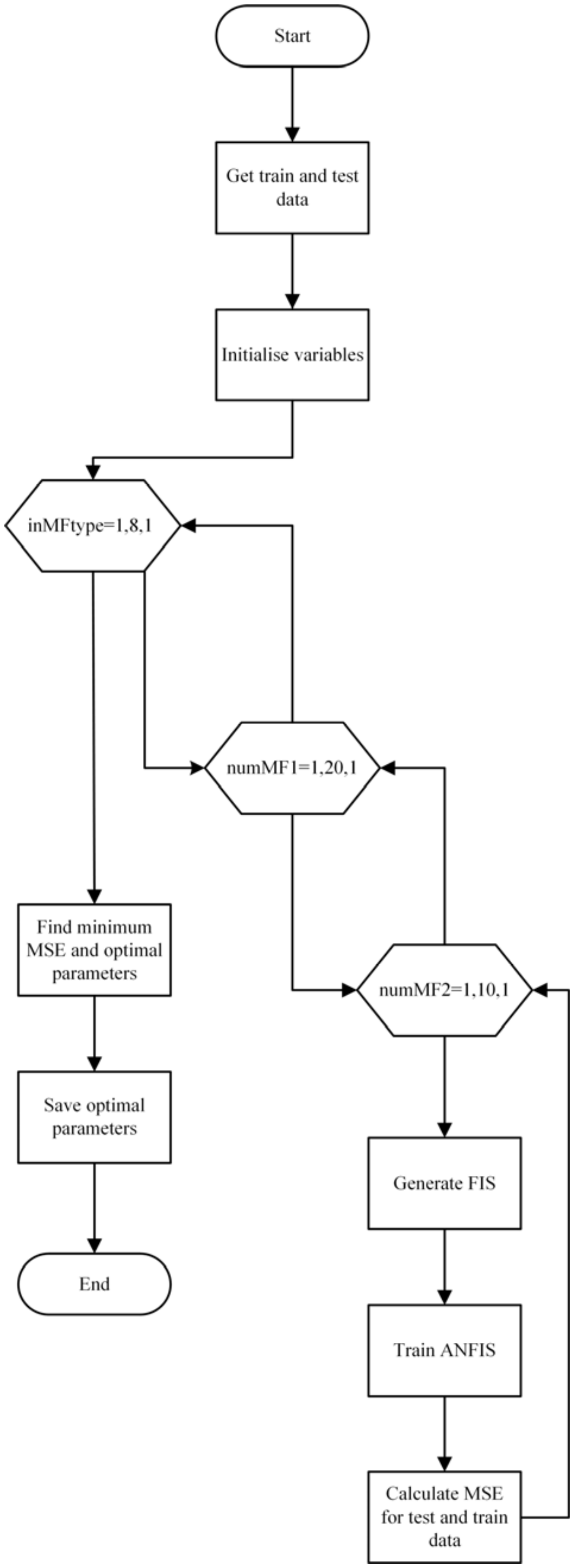

Figure 2. The flow chart of the suggested ANFIS based AGC-EDFA system

The last layer is the output layer that is a fixed layer and where the neuro-fuzzy system output is generated by the following equation: [46-52]

$$O_1^5 = \overline{w_1} f_1 + \overline{w_2} f_2 = = \frac{1}{w_1 + w_2}\begin{bmatrix} w_1(p_1 x + q_1 y + r_1) + \\ w_2(p_2 x + q_2 y + r_2) \end{bmatrix} = f \quad (5)$$

The details of the ANFIS method can be found in the literature [46-52]. In the proposed ANFIS architecture, a hybrid learning algorithm is used because it speeds up the learning process. The entire output *f* can be expressed as a linear combination of the sequence parameters. *f* is computed by the following equation:

$$f = \frac{w_1}{w_1 + w_2} f_1 + \frac{w_2}{w_1 + w_2} f_2 \quad (6)$$

$$f = \overline{w_1} f_1 + \overline{w_2} f_2 \quad (7)$$

$$f = (\overline{w_1} x) p_1 + (\overline{w_1} y) q_1 + (\overline{w_1}) r_1 + (\overline{w_2} x) p_2 + (\overline{w_2} y) q_2 + (\overline{w_2}) r_2 \quad (8)$$

The type of MFs and the number of input MFs should be determined to obtain the accurate ANFIS model. Firstly, the number of input MFs (inMFtypes) is tried for all MF types: between 1 and 10 for the first input (signal power (SP)) and between 1 and 20 for the second input (wavelength (W)). Errors are increased above these values. MF number of signal power and wavelength are called numMF1 and numMF2, respectively. Secondly, the data are trained with ANFIS for all MF types and the number of input MFs is determined. Thirdly, the test data are evaluated with the output FISs. Finally, all error rates and correlation coefficient (R) are calculated. In this work, the computed errors are mean absolute percentage error (MAPE), root mean square error (RMSE) and mean absolute error (MAE). The number of input MFs is chosen due to the minimum RMSE. Thus, the best number of input MFs is found for all MF types. The flow chart of the model of the ANFIS based AGC-EDFA system is shown in Fig. 2.

In this study, modeling is performed by using Sugeno-type FIS to model the pump laser current (PLC) on EDFA. Fig. 3 shows the ANFIS structure of the signal power (SP) and wavelength (W) values that are the two input parameters and PLC that is the output parameter. The employment of the developed software, type, weight, and the number of input membership functions are optimized. All the input membership functions were tried. For this purpose, we developed software to optimize the number of membership functions for the best results in each function. Finally, we obtained best results with generalized bell-shaped MFs. For this reason, only its results are presented in this paper.

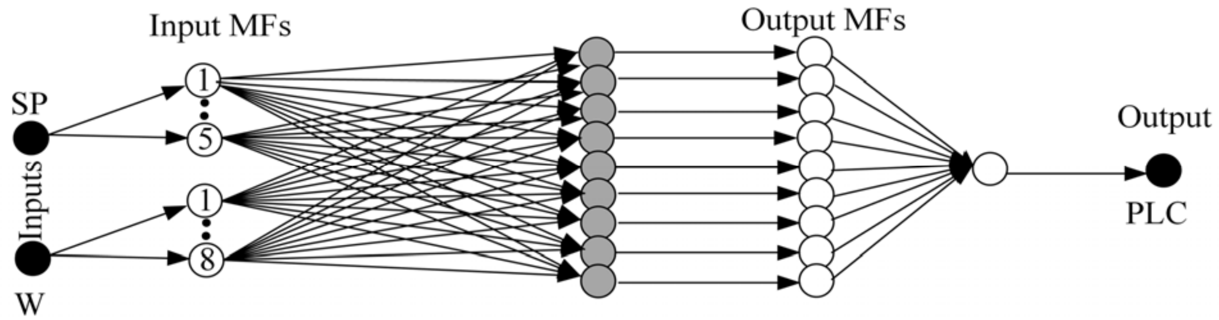

Figure 3. ANFIS architectures for the AGC-EDFA

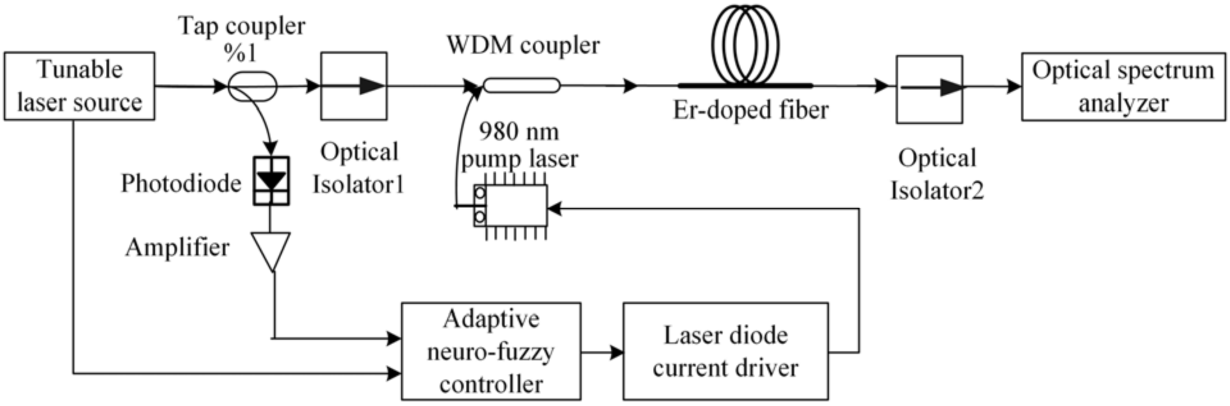

Figure 4. Proposed experimental ANFIS based AGC-EDFA setup

III. Experimental Setup

As it is mentioned before, the same data are used for the proposed configuration. The details of the used method can be found in [9, 20]. Fig. 4 shows the experimental setup for the measurement of the laser current demos. In this setup, the output signal powers are stable (30 dB in this study) for each wavelength. In this setup, a tunable laser source is used to obtain C-band laser signals. The laser signals are applied to the system one by one. The laser signal is divided by 1% to 99% in the tap coupler. 99% of the light is applied to optical isolator 1 and 1% is applied to the photodiode. C-band signals and pump signal are combined in the pump or WDM coupler and co-directionally pumped into the CorActive EMP 980 erbium-doped fiber (EDF) used in the forward direction by the butterfly laser pump, 100 mW. The output signal is measured by Anritsu 9710B optical spectrum analyzer with 0.07 nm resolution after passing optical isolator 2 which eliminates backscattering in EDF. The significant parameters of the EMP980 fiber are given in Table I. The level of the input signals is measured by the photodiode and the wavelength of the input signals is taken from the tunable laser source. These values are fed into the

ANFIS-based AGC-EDFA and the ANFIS-based AGC-EDFA changes the PLC to the desired constant power value.

TABLE I. THE PARAMETERS OF EMP980

Parameters	Values
Fiber length	13.5 m
Erbium concentration	227 ppm
Radius of erbium	1.68 μm
Radius od core	1.77 μm
Numerical aperture	0.19
Lifetime	10 ms

IV. Results and Discussion

In this paper, the ANFIS model is produced employing the grid partition method, and the generalized bell-shaped MF (gbellmf) is employed for the fuzzification of the input data since gbellmf has the best performance among other membership functions. All parameter values of the adaptive neurons are updated in each epoch to minimize the error. Fig. 5 shows the initial and final MFs of SP and W inputs developing the ANFIS model.

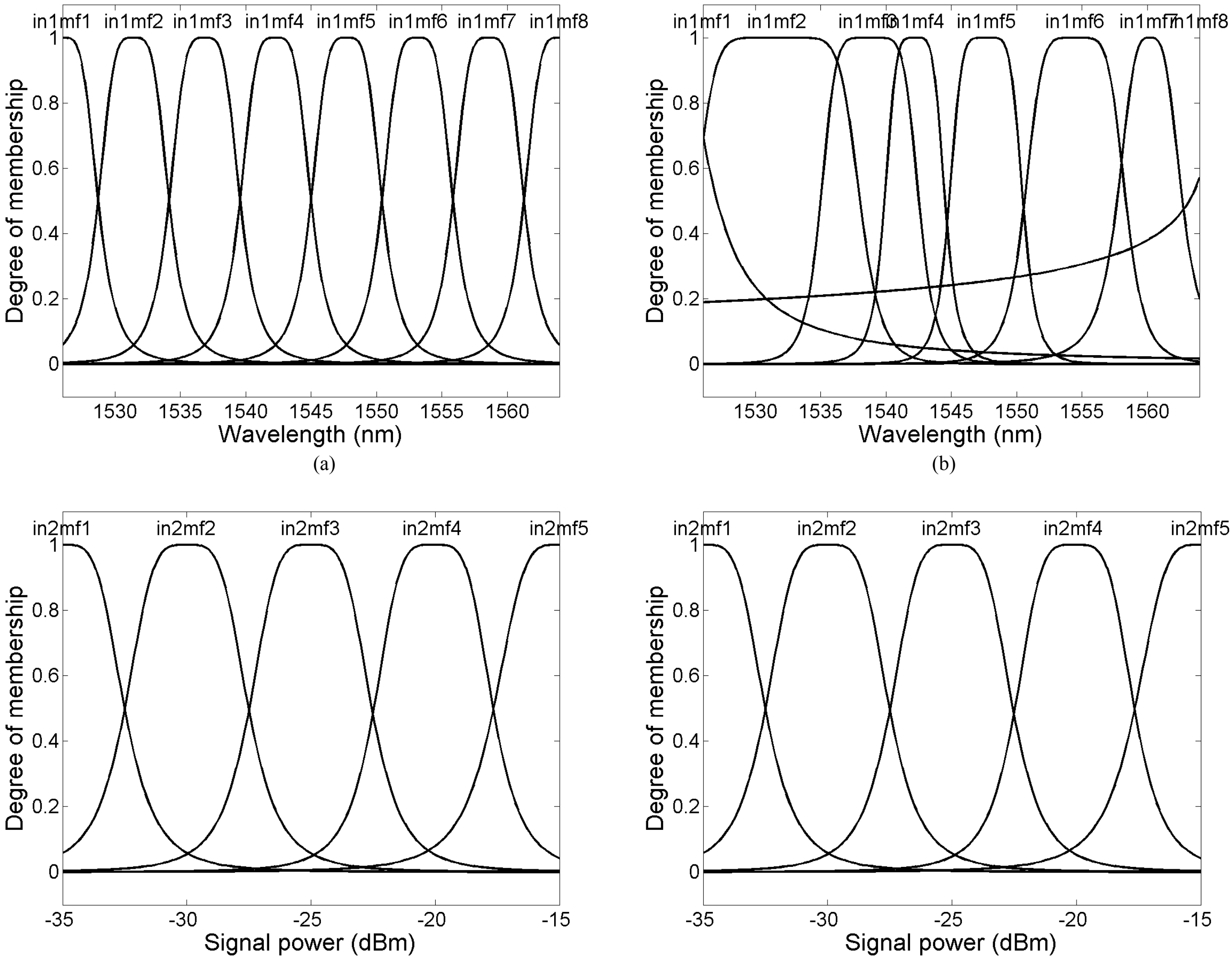

Figure 5. Initial and final MFs, (a) Initial MFs for the wavelength (b) Final MFs for the wavelength, (c) Initial MFs for the signal power (d) Final MFs for the signal power.

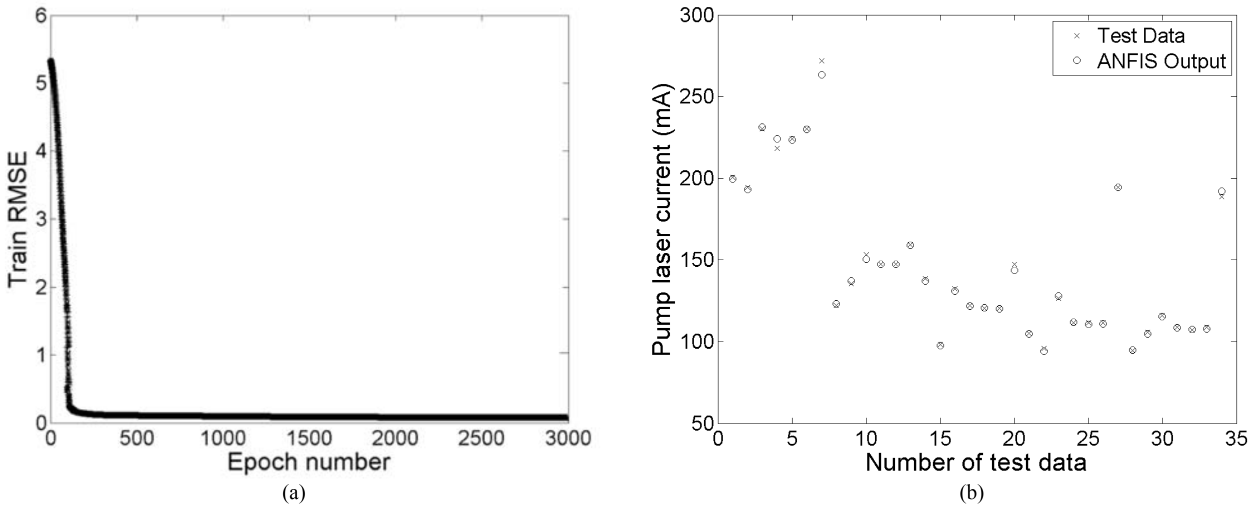

Figure 6. (a) Train error, (b) Test data versus ANFIS data

66 train data are used in 3000 training epochs. After training, the remaining 34 test data are employed to measure the precision of the proposed ANFIS-based model for the tuned PLC. Fig. 6 shows the training error for 3000 epochs and the comparison of the test data and ANFIS output, respectively. The results are tabulated in terms of the training and testing which are given in Table II. It is clearly seen that all results are highly accurate which validates the proposed technique. In addition to that, the square correlation coefficient (R^2) is close to the unity.

TABLE II. THE SQUARE CORRELATION COEFFICIENT AND RMSE OF THE TRAINING AND TESTING RESULTS

Results	R^2	RMSE
Training	0.99992105	0.01382771
Testing	0.99778293	0.09466907

V. CONCLUSION

The paper suggests the use of the ANFIS based AGC-EDFA for predicting the PLC. The main advantage of the suggested technique is the ability to forecast the PLC of EDFA. The results of the suggested model are quite consistent with the experimental results. Moreover, the suggested model can be used ergonomically for other rare doped optical amplifier applications.

In the fuzzy logic (FL) approach, the arrangements of the MFs are performed by the trial and error method [20] but in this approach, automatic tuning is achieved with the use of ANFIS. In addition to that, the results are both more accurate and training time is faster when compared to the FL method.

The developed ANFIS based AGC-EDFA is a computationally powerful, compatible with optimization and customizable method. The proposed scheme is single, simple, reliable and easily performed in practical applications.

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