Gain and noise figure of 20 dBm pumped macro-bending EDFA: a comparative study of numerical analysis with Artificial Neural Network model (ANN)

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In this work, performance analysis of macro-bending erbium doped fiber amplifier (EDFA) gain and noise figure are studied through theoretical and artificial neural network modeling (ANN) and compared to experimental results of both macro-bending case and normal case (without bending) of S. A. Daud et al. [1]. The calculations and simulation of ANN are performed at 15 m length of EDFA with 4 mm bending radius for the single mode fiber pumped at 980 nm in the C-band, with 20 dBm pump power and input signal power of -30 dBm. Our theoretical model shows a good agreement with the experimental data, with the advantage that the use of ANN reduces the computational time.

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1. Introduction

When erbium ions are doped in the fiber glass like silica, phosphate or other glasses to form as optical amplifier, there are many advantages for such amplifier; like high gain and low noise in the optical communication networks. It also provides a broadband amplification of signal whose wavelength is in the so-called third window for fiber-optic communication (1530 nm). This can be found in many researches of EDFA like that presented in [2].

Several reports have been made in recent years to extend the EDFA gain flatness, raise its value and lower its noise figure beyond the operating signal wavelength 1550-nm band which is important characteristic for wavelength division multiplexing (WDM) [3]. Like macro-bending EDFAs, the selective suppression of amplified spontaneous emission (ASE) in optical amplifier at certain regions has been done [4]. In particular, it has been found that the ASE of EDFA can be suppressed in the C-band region, and in some particular region of the S-band [5].

The ASE suppression methods in the C band are complex and expensive [5]. Later, it was shown that ASE can be suppressed in the C- band of EDFA using the fiber-bending losses instead of using additional new complex components in the amplifier module, by combination of a depressed cladding fiber properly bent and doped [7-10].

The ANN model for the gain of the EDFA with and without macro-bending has been considered for many advantages with emphasis on reducing the computational time and the complicated equations in solution .The computational Artificial Neural Network is arising from the different studies of the brain and nerves in biological systems. ANN shows a more accurate mathematical method for theoretical models and experimental procedures to understand the behavior of complex system with reduction of computational time taken by other programs in performing the computations which use complex equations to be solved [11].

The most useful characteristic of ANN is its ability to be understood by researcher in different fields of research. ANN is not programmed like any computer program, but is achieved by examples of patterns, observation and variable concepts; data which is qualified to learn. The process of qualifying is called training. The ANN organizes itself to treat an internal set of features to compare and classify data [12].

In this paper, the performance characteristics, gain and noise figure, of EDFAs with macro-bending of the fiber with 4 mm bending radius and 15 m fiber amplifier length and without bending for the single mode EDFA pumped at 980 nm with 20 dBm power, at -30 dBm input signal power in the C-band was investigated by theoretical and artificial neural network (ANN). Modeling is done using Levenberg-Marquardt algorithm [11–12] and is compared with experimental results in Ref. [1]. The theoretical results as well as ANN are in good agreement with the experimental data. Gain enhancement of about 12~14 dB is achieved with macro-bending at the wavelength region between 1480 and 1530 nm. The macro-bending also reduces the noise figure of the EDFA at wavelengths shorter than 1525 nm with a maximum improvement of 25 dB. So, the macro-bending improves the performance of the fiber amplifier. The dependence of the gain and noise figure of EDFA on macro-bending radius is done at room temperature.

2. Theory

EDFA is modeled as a three level system. But, due to the high relaxation rate of pump level (E_3, top level), it remains almost empty, therefore [13-15]

$$N_1 + N_2 = N_t \tag{1}$$

where N_1 is population density in ground state, N_2 is the population density in the metastable state and N_t is the total erbium-ion density in the core of EDFA. Then, the rate of change of population N_1 at ground level (energy E_1) is given as

$$\frac{dN_1}{dt} = \frac{\sigma_{pa} P_{SE} N_1}{a_p h \vartheta_p} + \frac{\sigma_{sa} P_{SE} N_1}{a_s h \vartheta_p} - \frac{\sigma_{se} P_{SE} N_2}{a_s h \vartheta_s} - \frac{N_2}{\tau_{sp}} \tag{2}$$

where P_{PE} is pump power, P_{SE} is signal power, σ_{pa} is absorption cross-section at pump frequency ϑ_p, σ_{sa} is absorption cross section at signal frequency ϑ_s, σ_{se} is emission cross section at signal frequency ϑ_s, a_p is cross sectional area for fiber modes for pump wavelength λ_p, as is cross sectional area for fiber modes for signal wavelength λ_s, and τ_{sp} is spontaneous emission lifetime for transition from E_2 to E_1.
Similarly, the rate of change of population N_2 at amplifier upper level is

$$\frac{dN_2}{dt} = \frac{\sigma_{pa} P_{SE} N_1}{a_p h \vartheta_p} + \frac{\sigma_{sa} P_{SE} N_1}{a_s h \vartheta_s} - \frac{\sigma_{se} P_{SE} N_2}{a_s h \vartheta_s} - \frac{N_2}{\tau_{sp}} \tag{3}$$

Under steady state condition, we have

$$\frac{dN_2}{dt} = 0 \tag{4}$$

Using Eq. (3) in Eq. (2) and after rearrangement, the expression becomes

$$\frac{N_2}{\tau_{sp}} = \frac{\sigma_{pa} P_{PE} N_1}{a_p h \vartheta_p} + \frac{P_{SE}}{a_s h \vartheta_s}\left[\sigma_{sa} N_1 - \sigma_{se} N_2\right] \tag{5}$$

Neglecting the contribution of spontaneous emission, the variation of pump power P_p and signal power P_s along the length of amplifier are calculated as [13]

$$N_{2avg} = \int_0^{L_E} N_2 dz = \int_0^{L_E} N_t \left[\frac{\left[\omega_p + \omega_{sa}\right]}{\left[\left(1/\tau_{sp}\right) + \omega_p + \omega_{sa} + \omega_{se}\right]}\right] dz$$

$$N_{2avg} = \frac{N_t\left[\omega_p + \omega_{sa}\right] L_E}{\left[\left(1/\tau_{sp}\right) + \omega_p + \omega_{sa} + \omega_{se}\right]_t} \tag{6}$$

where

$$\omega_p = \frac{\sigma_{pa} P_{PE}}{a_p h \vartheta_p} = \text{ pumping rate}$$

$$\omega_{sa} = \frac{\sigma_{sa} P_{SE}}{a_s h \vartheta_s} = \text{ stimulated absorption rate} \tag{7}$$

$$\omega_{se} = \frac{\sigma_{se} P_{SE}}{a_s h \vartheta_s} = \text{ stimulated emission rate}$$

Due to bending loss, one can write the rate equations for signal and pump power, respectively, as [14]

$$\frac{dP_{se}}{dz} = \Gamma_s(\sigma_{se} N_2 - \sigma_{sa} N_1) P_{se} - (\alpha + \alpha_{bent}) P_{se} \tag{8}$$

$$\frac{dP_{pe}}{dz} = \Gamma_p(-\sigma_{pa} N_1) P_{pe} - (\alpha' + \alpha_{bent}) P_{pe} \tag{9}$$

$$\text{with } N_1 + N_2 = N_t \text{ and } N_2 = N_t \frac{[\omega_p + \omega_{sa}]}{[\frac{1}{\tau_{sp}} + \omega_p + \omega_{sa} + \omega_{se}]} \tag{10}$$

where Γ_s, Γ_p are the overlap factors for signal and pump, respectively, for EDFA, P_{se}, P_{pe} are the powers of the signal and pump, σ_{se}, σ_{sa} are the emission and absorption cross sections for the signal, respectively. σ_{pae} is the absorption cross section of pump for EDFA, α, α′ are the background losses and α_{bent} is the loss due to macro-bending EDFA, ω_p is the pump rate, and ω_{se} and ω_{sa} are the rates of emission and absorption signals.

The analytical expression for the single mode fiber bending loss α can be expressed as follows [15-18]

$$\alpha_{bent}(\nu) = \frac{\sqrt{\pi} k_1^2 exp\left[-2/3(\frac{\gamma^3}{\beta^2}) R_{eff}\right]}{2\gamma^{\frac{2}{3}} V^2 \sqrt{R_{eff}} K_{\gamma-1}(\gamma a) K_{\gamma+1}(\gamma a)} \tag{11}$$

where a is the fiber core radius, $K_{v-1}(\gamma a)$ and $K_{v+1}(\gamma a)$ are the modified Bessel functions, $k_1 = [n_c^2 k^2 - \beta^2]^{1/2}$, $\beta = n_{cl} k[1 + b\Delta]$ is the propagation constant of the fundamental mode, $k(= 2\pi/\lambda)$ is the wave number of the signal with $\gamma = [\beta^2 - n_{cl}^2 k^2]^{1/2}$, $V = ak[n_c^2 - n_{cl}^2]^{1/2}$ is the normalized frequency and $\Delta = [n_c^2 - n_{cl}^2]/2n_c^2$, n_c and n_{cl} are the core and clad refractive indices, b is the fraction of the total electric field of the fundamental mode in the core [19].

$$R_{eff} = \frac{R}{1 - \frac{n^2}{2}[P_{12} - \nu(P_{11} + P_{12})]} \tag{12}$$

where n is the refractive index of the straight fiber, P_{11}(typically = 0.12) and P_{12}(typically = 0.27) are the components of the elasto-optical tensor and ν is the Poisson's ratio for fiber material (typically = 0.17) [19]. For silica fiber, $R_{eff}/R = 1.28$ [19]. Where R is the bending radius and R_{eff} is the effective bending radius.
Solving Eqs. (8-10) [15], one gets

$$P_{ose} = P_{ise} exp[-\Gamma_s \sigma_{sa} N_t L_E + \Gamma_s(\sigma_{sa} + \sigma_{se}) N_2 L_E - (\alpha + \alpha bent) LE \tag{13}$$

From Eqs. (5) and (11), one can write

$$P_{ose} = P_{ise} exp\left[\Gamma_s N_t L_E \left\{-\sigma_{sa} + (\sigma_{sa}+\sigma_{se})\frac{[\omega_p+\omega_{sa}]}{[\frac{1}{\tau_{sp}}+\omega_p+\omega_{sa}+\omega_{se}]}\right\} - (\alpha+\alpha bent)LE\right] \quad (14)$$

where P_{ise} and P_{ose} are, respectively, the powers of input and output signal from macro-bending EDFA and L_E is the EDFA length.

The EDFA gain is given as [15]

$$G(dB) = 10log_{10}\left(\frac{P_{ose}}{P_{ise}}\right) \quad (15)$$

The noise figure, NF, can be calculated in decibels through [15]

$$NF(dB) = 10log_{10}\left(\frac{1}{G}+\frac{P^0_{ASE}(\lambda_s)}{Gh\nu_s}-\frac{P^i_{ASE}(\lambda_s)}{h\nu_s}\right) \quad (16)$$

where P^0_{ASE}, P^i_{ASE} are, respectively, the output and input ASE spectral densities.

3. Calculations

3.1. Theoretical model

The aim of this work is to compare the theoretical calculation of the gain and noise figure dependency of macro-bending EDFA pumped by 980 nm with a new model ANN. To calculate the gain and noise figure, we solved Eqs. (14) and (16) with the help of Eqs. (1-13) using Rung-Kutta method. The theoretical results and ANN results are compared with the experimental results obtained for macro-bending EDFAs at room temperature by S. A. Daud et al. [1].

To perform numerical calculations, we choose an Alumina-silica erbium-doped fiber as a gain medium of an amplifier operating at a pump wavelength λ_p = 980 nm and a fixed input pump power of ~ 100 mW. The signal wavelength λ_s = 1530 nm and its power $P_s(0)$ is taken as 10 μW as listed in Ref. [20].

3.2. Neural network architecture of EDFA

To provide the simulation with an ANN, one needs to run three steps :(1) the neuron model, as a first step which is a single processing unit, (2) the network architecture, which provides the different connections of the processing units, and (3) the learning algorithm, which evaluates the weights of the connections. Each neuron has an activation function that provides the link among the input and output [11]. The activation function is a linear or semi-linear function, and is smoothly limiting threshold (sigmoid function). When a neuron got an input signal, it produces the corresponding output result, as a result of the activation function, of the neuron, according to [11, 12]. Figure 1 shows a multilayer neural network architecture of EDFA gain and noise figure with and without macro-bending respectively. The ANN model is simply shown as a block diagram in Fig. 1.

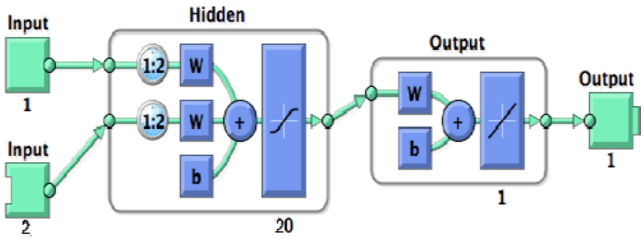

Fig. 1. Neural network architecture of EDFA.

The proposed ANN model of the output measurements for macro-bending EDFA can be viewed as two inputs and one output model (for gain and for noise). The inputs are the signal wavelength in (nm) and the signal loss power in (dB/m) due to macro-bending, while the output is the EDFA gain and noise figure in (dB).
The network 2-20-20-1 and the equation representing the model is [11]

$$G = purelin[\{net.Lw(3,2).trans.\{net.Lw(2,1)\}.trans.\{net.Lw(1,1).(\lambda_s, Loss + net.b(1)) + net.b(3)\}\}] \quad (17)$$

where purelin is the linear transfer function used in ANN, net.Lw(3,2) is the linked weights between the second hidden layers and the output layer which is the macro-bending gain and noise figure. net.Lw(2,1) is the linked weights between the first hidden layer and the second layer. net. Lw(1,1) is the linked weights between the inputs and the first hidden layer. net. b(1), net. b(2) and net. b(3) are the biases of the first, second hidden layers and the output, respectively.

Tables 1 and 2, respectively, list the fiber parameters used for the bend loss calculation [18] and used for gain and noise calculations [15].

Table 1. Fiber parameters used for the bend loss calculation [18].

Symbol	Definition	Value
a	core radius	1.346 μm
b	fraction of the total electric field	0.02
n_c	core refractive index	1.446
n_{cl}	clad refractive index	1.400
λ	signal wavelength	1.53 μm
NA	numerical aperture	0.3618

Table 2. The fiber parameters used in gain and noise calculations [15].

Symbol	Definition	Value
σ_s^e	signal emission cross section	5.79×10^{-25} m^2
σ_s^a	signal absorption cross section	6.97×10^{-25} m^2
σ_p^e	pump emission cross section	0.87×10^{-25} m^2
σ_p^a	pump absorption cross section	2.44×10^{-25} m^2
τ	life time of Er ions	10.8 ms
N	erbium concentration	2.4×10^{25} m^{-3}
λ_s	signal wavelength	1530 nm
λ_p	pump wavelength	980 nm
ν_s	signal frequency	1.96×10^{14} Hz
ν_p	pump frequency	3.06×10^{14} Hz
$P_{ASE}^{+}(L)$	co-propagation ASE power	0.15 mW
α_s	signal absorption constant	0.5 m^{-1}
L	amplifier length	0-35 m
P_p^i	input pump power	100 mW

Our model of training contains two hidden layers, 20 neurons, two input and one output. The training performance of the ANN model is performed by the algorithm used the Levenberg-Marquardt (LM) [11]. In this work, after the training stage, the choice of the ANNM with the best performance is based on the evaluation of the mean square error (MES) on the validation set. Therefore, we used it because it has the smallest mean square error (MSE) value. The main information about the training is reported in Table 3.

Table 3. Main data of the training of ANN model [11].

Definition	Value
Number of training vectors	2948
Number of validation vectors	631
Number of testing vectors	631
Neurons of 1st hidden layer	20
Neurons of 2nd hidden layer	20
Training algorithm	Levenberg-Marquardt
Training epochs	150
Activation function of the hidden layers	Hyperbolic tangent
Activation function of the output layers	Linear

The experiment has been done by S. A. Daud et al. [1]. The EDF is pumped by a 980-nm laser diode using a co-propagating pump scheme. The commercial EDF used is 15 m long with an erbium ion concentration of 440 ppm. A tunable laser source is used to characterize the amplifier in conjunction with an optical spectrum analyzer. The amplifier is characterized in the wavelength region between 1480 to 1560 nm in terms of the gain and noise figure under changes in the optical power. Before the amplifier experiment, the optical loss of the EDF was characterized for both cases with and without macro-bending. The macro-bending is obtained by winding the EDF in a bobbin (special confinement) with various radiuses between 0.35 and 0.50 mm.

4. Results and discussion

Our proposed ANN model of macro-bending EDFA is representing by two-input one-output model, Fig.3. The inputs are: the signal wavelength (1480 – 1560 nm) and the loss by bending in dB/m, while the output is: gain G (dB) and noise figure (NF) in dB. As mentioned, the proposed ANNs were trained using LM optimization technique. A two hidden layers network structure of 20 and 20 neurons and the output layer consisting of one neuron are used as shown in Table 3. Figure 2 shows the variations of the overall mean square errors for the training and validation of the data with respect to the number of epochs for LM algorithm.

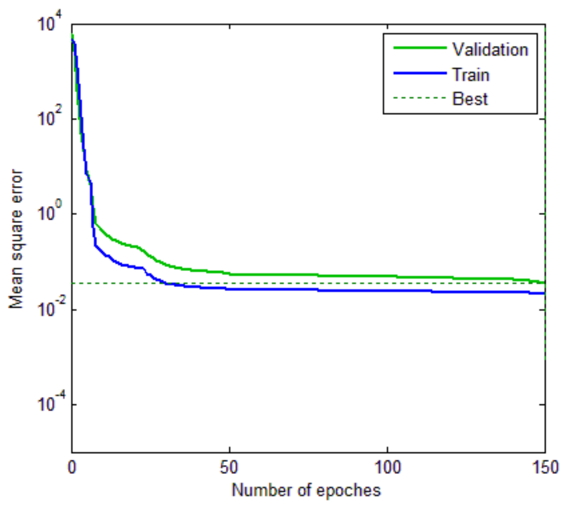

Fig. 2. The variation of the MSE error with the number of epochs.

The fiber losses of erbium doped fiber are calculated as a function of signal wavelength. Figs. 3 and 4 show the spectral variation of the gain against the input signal wavelength for EDFA with and without macro-bending, respectively. The amplifier length is 15 m and bending radius 4 mm at -30 dBm input signal power and 100 mW pump power.

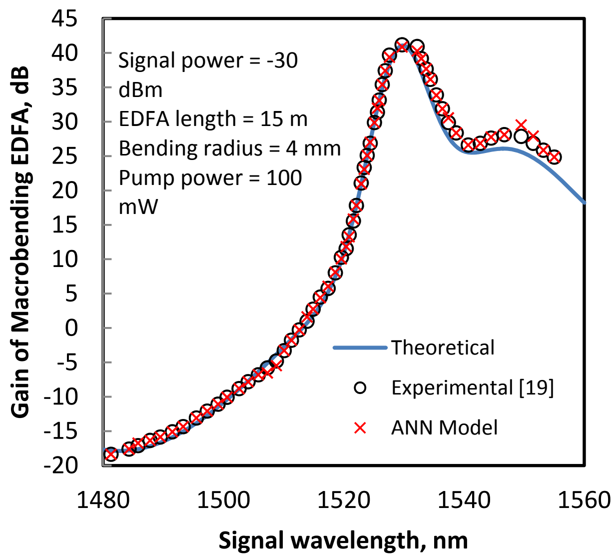

Fig. 3. Gain spectra with macro-bending effect. The input signal and pump powers are fixed at -30 dBm and 100 mW, respectively.

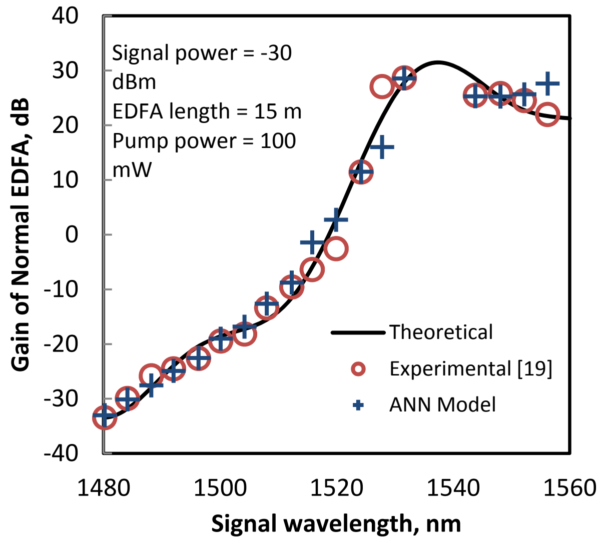

Fig. 4. Gain spectra without the macro-bending effect. The input signal and pump powers are fixed at -30 dBm and 100 mW, respectively.

The symbol ○ is the experimental data for the gain of EDFA with and without macro-bending respectively [1]. The symbols × and + are the ANN training data for the gain of EDFA with and without macro-bending, respectively. The blue and black lines respectively are theoretical model for the gain of EDFA with and without macro-bending, respectively. As shown in Figs.3 and 4, the gain is enhanced by 12-14 dB with macro-bending at the wavelength region 1510-1560 nm. This enhancement is due to the macro-bending effect which suppressing the ASE in this region.

In the case of macro-bending, the positive values of the gain are observed for an input signal wavelength of 1516 nm or above. Many tries and training are done to find the best values of ANNM using low numbers of epochs, hidden layers and neurons. Simulation results of micro-bending gain using ANN are verified with experimental data which showing an excellent fitting and excellent performance.

Furthermore, the macro-bending reduces the noise figure of the EDFA at wavelength shorter than 1525 nm are shown in Figs.5 and 6.

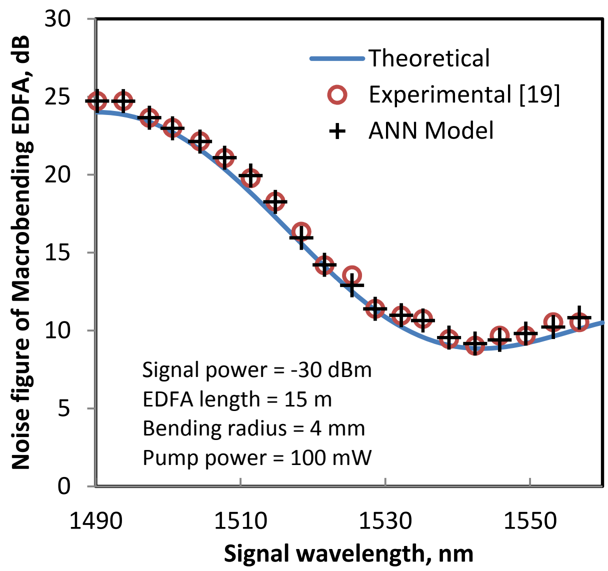

Fig. 5. Noise figure spectra with the macro-bending effect. The input signal and pump powers are fixed at -30 dBm and 100 mW, respectively.

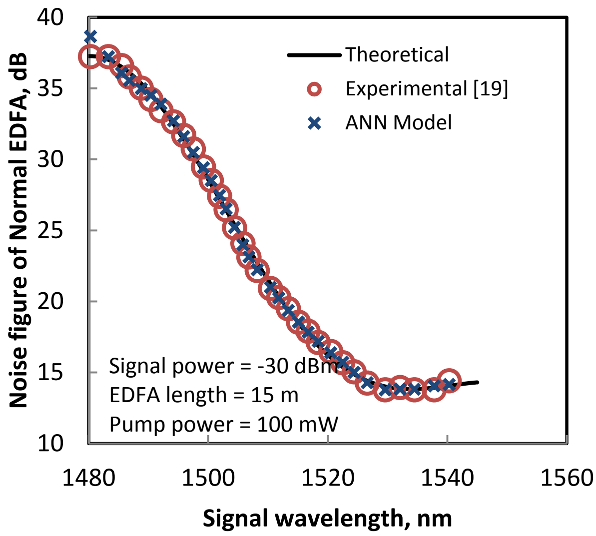

Fig. 6. Noise figure spectra without the macro-bending effect. The input signal and pump powers are fixed at -30 dBm and 100 mW, respectively.

Figs. 5 and 6, respectively, show the spectral variation of the noise figure with and without microbending, against the input signal wavelength for EDFA with macro-bending for amplifier length 15 m and bending radius 4 mm, at input signal power -30 dBm and pump power 20 dBm. The symbols ○ and + are the experimental data and ANNM for the gain of EDFA with macro-bending, respectively [1]. The blue line is the theoretical model for the gain of EDFA with macro-bending. There is an excellent agreement between ANNM and experimental results, where ANNM proves its high performance rather the theoretical model. The ANN model provides high accurate outputs for given inputs without any need to solve mathematical equations between input and output data. The trained method for ANNM is performed with 150 epochs and 40 neurons. It can be used as a simulation method for the EDFA performance calculations.

5. Conclusion

In this work, we study the dependence of both gain and noise figure of EDFA on macro-bending. The study is performed for 20 dBm pump at 980 nm in the wavelength region 1510-1560 nm, at fiber bending radius 4 mm, -30 dBm signal power and amplifier length 15 m using a theoretical model and ANN. Improvements are achieved for the performance of macro-bending EDFA. The macro-bending suppresses the ASE at longer wavelengths to improve the gain at the shorter wavelength 1525 nm. The ANN modeling provides an excellent method to obtain accurate simulation for EDFA. The proposed ANN can be used to model EDFA performance and simulation results show an excellent agreement with experimental data and with low computational time.

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