Temperature dependence performance of macro-bending erbium doped fiber amplifier

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We present in this work the dependence of the macro-bending EDFAs Gain and noise figure on the temperature, where the dependence of both gain and noise of macro-bending EDFA and without macro-bending are calculated for the temperature range (-40 to 60^{0}C) with bending radius 4 mm for the case of amplifier with bending single mode EDFA pumped at 980 nm. We obtained improvements for the gain and noise figure of macro-bending EDFA due to bending loss as well as temperature changes. where the gain increase to ~ (2- 6 dB) for the amplifier length (5-15m) at temperatures +20, -20 and 60 ^{0}C and the maximum value of the gain was ~ 16 dB at amplifier length 20 m at this range of temperatures. furthermore the noise figure is reduced by ~ 5 dB with macro-bending for amplifier length L= 25 m and by ~ 34 dB at 30 m of amplifier length at the temperatures -40, +20 and +60 ^{0}C. Finally, the gain is higher by ~ 5 dB when the temperature increases from -40 to 60 C with macro-bending at a wavelength 1540 nm, and the noise figure reduces at the wavelength 1540 nm by ~ 0.44 dB for temperature changes from -40 to 60 ^{0}C for macro- bending EDFA.

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1. Introduction

Erbium doped fiber amplifiers (EDFAs) have been demonstrated from many years and many studies were done to improve its characteristics, such as gain, noise figure and optical signal to noise ratio (OSNR). One important advantage of this amplifier is a broadband amplification of radiation whose wavelength is in the so-called third window for fiber-optic communication (1530 nm). In addition, the temperature dependence of the gain characteristics of EDFAs has also of great importance for WDM systems [1, 3].

Many researches have been made in recent years to extend the gain flatness of erbium-doped fiber amplifiers (EDFAs) beyond the traditional 1550-nm band which is important characteristic for wavelength division multiplexing (WDM) [1, 2]. S. A. Daud et al. work on macro-bending EDFAs, in there work the selective suppression of ASE in optical amplifier at certain regions has been suggested, In particular, it has been demonstrated that the ASE of erbium-doped fibers amplifier can be suppressed in the C-band region, to the advantage of the S-band region amplification [3, 4].

The noise reduction in the C band is doing by inserting multiple filters within the amplifier module but this way has disadvantages such as increasing the complexity of the circuits and high cost components required [4, 5]. Later, it was shown that ASE can also be suppressed using the fiber-bending losses instead of additional new component in the amplifier module, by combination of a depressed cladding fiber properly bent and doped [4, 6].

A number of mathematical models with different complexities have been proposed to analyze the behavior of EDFAs [7]. Optical quantities generally require a large amount of computational time by using different theories, approximations, assumptions and rough estimations of some parameter values .In addition to that there are different and numerous expensive experimental optical setups which are not easy to achieve accurate values for various reasons. Also, there are sometimes considerable differences between theoretical and experimental values in the optical related system [8, 9].

In this paper, the dependence of both gain and noise of macro-bending EDFA and without macro-bending are calculated for the temperature range (-40 to 60^{0}C) with bending radius 4 mm for the case of amplifier with bending for the single mode EDFA pumped at 980 nm. We obtained improvements for the gain and decrease values of noise figure for macro-bending case, and our calculations of temperature show a dependence of macro-being EDFA on the temperature, so we can obtain another improvement for gain and noise figure reduction with temperature changes.

2. Theory

2.1 Bent fiber

The coefficient of bending loss α_b in single mode fibers with step index profiles was developed by Marcuse, according to Marcuse; the total loss of a macro-bent fiber is [3- 5]

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

where a is the radius of the fiber core, $K_{\nu-1}(\gamma a)$ and $K_{\nu+1}(\gamma a)$ are the modified Bessel functions [3-5] $k_1 = [n_c^2k^2 - \beta^2]^{1/2}$, $\beta = n_{cl}k[1 + b\Delta]$ is the propagation constant of the fundamental mode, $k = 2\pi/\lambda$ is the wave number of the signal with $\gamma = [\beta^2 - n_{cl}^2k^2]^{1/2}$, $V = ak[n_c^2 - n_{cl}^2]^{1/2}$ and $\Delta = [n_c^2 - n_{cl}^2]/2n_c^2$, n_c and n_{cl} are the core and clad refractive index, b is the fraction of the total electric field of the fundamental mode in the core [10-14]. The values of a, λ, b, n_c and n_{cl} are listed in Table 1.
With

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

for silica fiber, $R_{eff}/R = 1.28$, which the refractive index of a stress bend fiber n_b is given as

$$n_b = n_{material}.\exp(\frac{x}{R}) \cong n_{material}(1 + \frac{x}{R}) \quad (3)$$

where R is the fiber bend radius and x is the position on bend direction. The physical refractive index of the fiber will change after the bending, so the stress-optic effect causes the material refractive index distribution to change as follows [3-5]

$$n_{material} = n\left[1 - \left(\frac{n^2x}{2R}\right)[P_{12} - \nu(P_{11} + P_{12})]\right] \quad (4)$$

where n is the refractive index of the straight fiber, P_{11}(typically 0.12) and P_{12}(typically 0.27) are components of the elasto-optical tensor and ν is the Poisson's ratio for fiber material(typically 0.17) [10, 11].

2.2 Model of EDFA with macro-bending

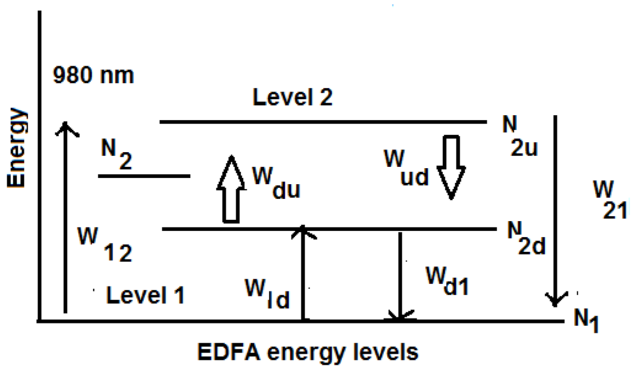

Fig. 1. Energy levels of EDFA and the transitions rates for the two level system

Consider two level system for EDFA as in Fig. 1, the ground state populate with N_1 erbium ions and the metastable second level divided to two sublevels, the upper level populate with N_{2u} and the lower level with N_{2d} erbium ions, the transition from N_{2u} to N_{2d} is non-radiative, with non radiative rates W_{du} and W_{ud} for lower and upper sublevels. The stimulated rates for absorption and emission processes in the levels N_1 and N_2 are W_{12} and W_{21}, also the spontaneous emission rates for pump absorption and emission between the levels N_1 and N_{2d} are W_{1d} and W_{d1}. The rate equations of EDFA model is obtained in refs. [2, 3, 12], can be written as follows:

$$\frac{dN_{2u}}{dt} = W_{1d}N_1 - W_{d1}N_{2+} + W_{du}N_{2d} - W_{ud}N_{2u} \quad (5)$$

$$\frac{dN_{2d}}{dt} = W_{12}N_1 - W_{21}N_{2d} - \gamma N_{2d} - W_{du}N_{2d} + W_{ud}N_{2u} \quad (6)$$

$$\frac{dN_1}{dt} = W_{d1}N_{2u} - W_{1d}N_1 + W_{21}N_{2d} - W_{12}N_1 + -\gamma N_{2d} \quad (7)$$

Under the steady state conditions all the derivatives with time in equations 5, 6 and 7 equal to 0, this gives

$$N_{2d} = \tau\left[\left(\sigma_p^aN_1 - \beta_s\sigma_p^eN_{2d}\right)\frac{I_p}{h\nu_p} + \begin{pmatrix}\sigma_s^aN_1 - \\ \sigma_s^eN_{2d}\end{pmatrix}\frac{\left(I_s+I_{ASE}^{\pm}\right)}{h\nu_s}\right] \quad (8)$$

with

$$\beta_s = \frac{N_{2u}}{N_{2d}} = \frac{W_{ud}}{W_{du}} = e^{(-\frac{\Delta E}{K_BT})} \quad (9)$$

here K_B is Boltzman's constant, T is the temperature in Kelvin, $\Delta E_2 = E_{2u} - E_{2d}$ is the energy difference between the sublevels N_{2u} and N_{2d}, $\sigma_s^{a,e}$ is the absorption and emission cross-section of the signal, and $\sigma_p^{a,e}$ is the absorption and emission cross-section of the pump, respectively, $\nu_{p,s}$ is the pump and the signal frequencies, I_s and I_p are signal and pump intensities and $I_{ASE}^{\pm}$ is the forward (+) and backward (-) amplified spontaneous emission (ASE) of propagating optical intensities.
with $N_T = N_1 + N_{2d} + N_{2u}$, the total erbium ion density or $N_T = N_1 + (1 + \beta_s)N_{2d}$ eqn. 9 rewritten as

$$N_{2d} = N_T\left[\frac{\frac{\tau\sigma_p^aI_p}{h\nu_p}+\frac{(I_s+I_{ASE}^{\pm})\sigma_s^a\tau}{h\nu_s}}{(1+\beta_s)\frac{\tau\sigma_p^aI_p}{h\nu_p}+\beta_s\frac{\tau\sigma_p^eI_p}{h\nu_p}+(1+\beta_s+\eta)\frac{(I_s+I_{ASE}^{\pm})\sigma_s^a\tau}{h\nu_s}+1}\right] \quad (10)$$

with $I_s(r,z) = P_s(z)\frac{e^{-[\frac{r^2}{W_o^2}]}}{\pi w_o^2}$, $I_p(r,z) = P_p(z)\frac{e^{-[\frac{r^2}{W_o^2}]}}{\pi w_o^2}$ and

$$I_{ASE}{}^{\pm}(r,z) = P^{\pm}{}_{ASE}(z)\frac{e^{-[\frac{r^2}{W_o^2}]}}{\pi w_o^2} \quad (11)$$

where $P_s(z)$ and $P_p(z)$ are the signal and pump powers, w_o is the optical spot size and $P^{\pm}{}_{ASE}(z)$ is the power of amplified spontaneous emission and $\eta = \frac{\sigma_s^e}{\sigma_s^a}$ is the ratio between signal emission and absorption cross section [2, 12].

Consider the power of the signal, pump and ASE are P_s, P_p and $P_{ASE}^{\pm}$, we can write the propagation equation as [2, 12]

$$\frac{dP_s}{dz} = 2\pi\sigma_s^a P_s(z)(\eta + 1 + \beta_s) \times \left(-\frac{\tau}{2\pi\left(\frac{A}{\Gamma} - 2\pi\sigma_s^e\right)}\left[\frac{1}{h\nu_p}\frac{dP_p}{dz} + \frac{1}{h\nu_s}\left(\frac{dP_p}{dz} + \frac{dP_{ASE}^{\pm}}{dz}\right)\right]\right) - P_s(z) \propto_T \quad (12)$$

where Γ is the overlapping factor, $\alpha_T = \propto_s + \alpha_b(\nu)$ is the total losses of the signal and α_s is the background loss of the signal, A is the effective doped area and $\eta = \frac{\sigma_s^e}{\sigma_s^a}$. The input signal can written as $P_s^{int} = \frac{h\nu_s(A - 4\tau\Gamma\sigma_s^e)}{\tau\sigma_s^a(\eta + 1 + \beta_s)}$ which is a function of temperature [2, 12].

At the boundary condition in the +ve direction $P_{ASE}^{-}(0) = 0, P_{ASE}^{-}(L) = 0$ and $P_{ASE}^{+}(0) = 0$, so the gain can be obtained by the following equation [2, 12]:

$$G = \exp(-\alpha L) \times exp\left[\frac{h\nu_s}{P_s^{int}}\left(\frac{P_p(0) - P_p(L)}{h\nu_p} + \frac{P_s(0)}{h\nu_s}(G - 1) - \frac{P_{ASE}^{+}(L)}{h\nu_s}\right)\right] \quad (13)$$

We can measure P_s^{out} and P_p^{out} for a given P_s^{in} and P_p^{in} for maximal pumping efficiency [3, 12].

$$P_p^{out} = P_p(L) = \frac{1}{R\left(\frac{\eta}{b_p^a} - \frac{\beta_s}{b_p^e}\right)} \quad (14)$$

where $R = \frac{\int_0^\infty N_t(r) f(r) r dr}{\int_0^\infty N_t(r) r dr}$. It is note that the output pump power is a function of the temperature, $b_p^{a,e} = h\nu_{p/\tau\sigma_b^{a,e}}$, ν_p is the pump frequency and $\sigma_b^{a,e}$ is the stimulated absorption and emission cross section of the pump beam.

The noise figure can be calculated in decibels (dB) through the given equation:

$$NF(dB) = 10log_{10}\left(\frac{1}{G} + \frac{P_{ASE}^0(\lambda_s)}{Gh\nu_s} - \frac{P_{ASE}^i(\lambda_s)}{h\nu_s}\right) \quad (15)$$

where P_{ASE}^0, P_{ASE}^i are the output and input ASE spectral density respectively.

3. Results and discussion

We use Matlab simulation analysis to calculate the temperature dependency of macro-bending EDFAs pumped by 980 nm. The gain and noise of bent fiber at radius 4mm for fiber lengths are calculated in the following manner; we calculate the loss coefficient from Eqs.1-4, the input data given in Table 1, the output power in Eq. (14) is calculated with different temperature values for the fiber length of 5- 35 m. The fiber parameters values are selected for an Al/P-silica erbium doped fiber amplifier and presented in Table 2 [13- 15]. The cross section ratio of the signal beam depends on temperature. The parameter η was calculated at different temperatures according to McCumber's theory and presented in Table 3.

We choose a silica erbium-doped fiber as a gain medium of an amplifier operated at the pump wavelength λ_p = 980 nm and the input pump power is fixed about 100 mW at the length L = 0. The signal wavelength λ_s = 1530 nm and its power $P_s(0)$ is taken as -30 dBm as listed in Table 2 [2,12]. From the analysis of the results, our model gives good agreement with the experimental results of macro-bending EDFAs at room temperature by S. A. Daud et al. [3].

Table 1. The parameters of the bend loss calculation

Symbol	Definition	value
a	core radius	1.346 μm
b	the fraction of the total electric field	0.20
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 [2, 12]

Symbol	Definition	value
σ_s^e	signal emission cross section	8×10^{-25} m^2
σ_s^a	signal absorption cross section	7×10^{-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	0.018 s
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	Back ground loss	0.5 dBm^{-1}
L	fiber length	5-35 m
P_p^i	input pump power	100 mW

Table 3. The input parameters for temperature calculations

^{0}C	β_s	η	$P_p^o(L)$	P_s^{int}	
-20	0.206	0.945	3.308 mW	0.493 mW	Ref.[3]
+20	0.322	0.855	3.211 mW	0.475 mW	Ref.[3]
+60	0.444	0.972	3.344 mW	0.482 mW	Ref.[3]

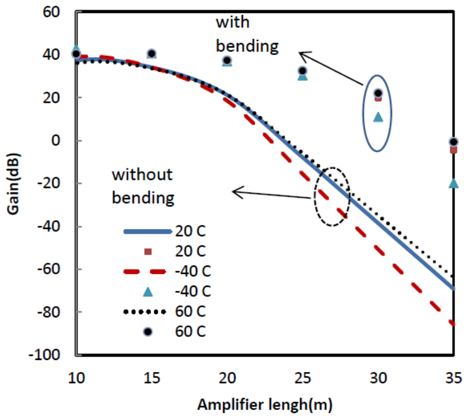

Fig. 2. Gain vs amplifier length with bending loss and without bending loss for different values of temperature (-40, +20 and +60 ^{0}C), at input signal and pump power, -30 dBm and 100 mW, respectively

Fig. 2 shows the signal gain plotted as a function of the amplifier length for (with and without macro-bending fiber) at temperatures -40, +20 and +60 ^{0}C. It is clear from the figure that the signal gain of macro-bending fiber increases than that without bending by ~ (2- 6 dB) for the amplifier length from (5-15m) at temperatures +20, -20 and 60 ^{0}C, the maximum value for the gain increasing is ~ 16 dB at amplifier length 20 m at this range of temperatures. The increase in gain due to macro-bending loss, which suppresses the ASE and resulted in an increase in the EDFA gain at wavelength 1530 nm for the fiber length between 5-35m.

Fig. 3 shows the variation of the noise figure with both temperature and fiber length for the EDFA with and without macro-bending. The input signal and pump power are fixed at -30 dBm and 100 mW, respectively. The bending radius is set at 4 mm in the case of the amplifier with macro-bending. As shown in the Fig. 3, the noise figure is reduced by about 5 dB with macro-bending at amplifier length L= 25 m and by ~ 34 dB at 30 m of amplifier length at the temperatures -40, +20 and +60 ^{0}C . Also the temperature ineffective length is L< 25 m, but the temperature more effective for L> 25 m, where the noise decrease as the temperature increase for fiber with and without macro-bending, these results can be shown clear in Fig.4b for macro-bending effect.

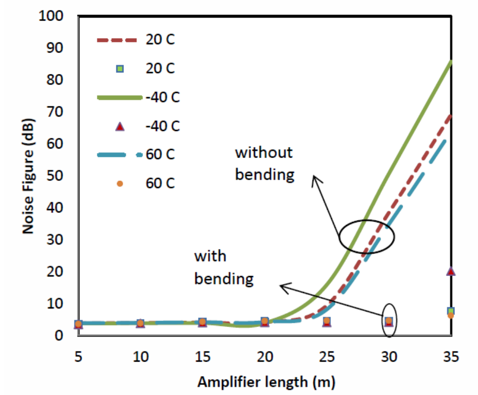

Fig. 3. Noise figure vs amplifier length for the bending and non bending amplifier for different values of temperature (-40, +20 and +60 ^{0}C), at the input signal and pump power is fixed at -30 dBm and 100 mW, respectively

Also it is noted that the signal gain for fiber with macro-bending effect decrease with increasing temperature, when the fiber length L< 15m and the gain not affected for both fiber with and without macro-bending effect with increasing temperature when the fiber length between 15-20m. And finally the signal gain increases for both fiber with and without macro-bending effect with increasing temperature when the fiber length 20< L< 35m as in Fig. 4a

The noise figure changes slowly with temperature increases in the amplifier range 5 – 25m and the higher values of noise occur at 35 m of amplifier length at -40, 20 and 60 ^{0}C for without macro-bending case as in Fig. 4b. The variations of the gain and noise figure with the temperature for 20m and 35 m for the case of bending and without bending are given in Tables 4 and 5.

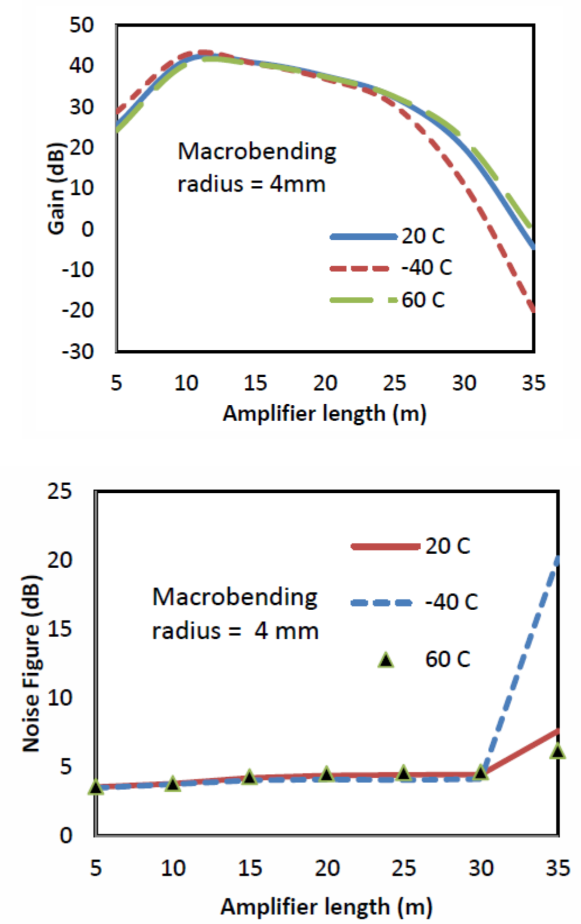

Fig. 4. Gain and noise figure as function of amplifier length with the macro-bending effect for different values of temperature (-40, +20 and +60 ^{0}C). The input signal and pump power is fixed at -30 dBm and 100 mW, respectively

Table 4. The variation of gain and noise figure at temperature range in our model for amplifier length 20 m

T (^{0}C)	Without bending EDFA		With Bending EDFA	
	G (dB)	NF(dB)	G (dB)	NF(dB)
-40	18.5	3.9	36.9	4.1
20	21.2	4.11	37.6	4.4
60	21.4	4.22	37.4	4.5

Table 5. The variation of gain and noise figure at temperature range in our model for amplifier length 35 m

T (^{0}C)	Without bending EDFA		With Bending EDFA	
	G (dB)	NF(dB)	G (dB)	NF(dB)
-40	-85	85	-19.8	20
20	-69	69	-4.4	7.6
60	-63	63	-0.62	6.18

The values of the gain in Table 5 are negative for length of amplifier > 30 m at different temperature ranges and these values are improved due to macrobending effect

Fig. 5 shows the optical signal to noise ratio (OSNR) plotted as function of macro-bending amplifier length at temperatures (-40, +20 and +60 ^{0}C). The input signal and pump power is fixed at -30 dBm and 100 mW, respectively. OSNR nearly constant for amplifier length (5 – 20 m), then increases with temperature at amplifier length (21 – 35 m) and decrease with amplifier length (25-35) at all values of temperature, it is noted that lower values of OSNA corresponding to higher values of the gain.

Fig. 6 shows the spectral variations of optical signal to noise ratio (OSNR) for macro-bending EDFA at temperatures (-40, +20 and +60 ^{0}C). The input signal and pump power is fixed at -30 dBm and 100 mW, respectively.

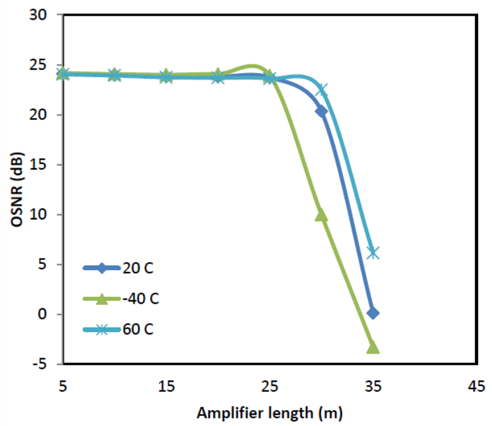

Fig. 5. The optical signal to noise ratio (OSNR) vs the amplifier length with the macro-bending effect for different values of temperature (-40, +20 and +60 ^{0}C). At input signal and pump power, -30 dBm and 100 mW, respectively

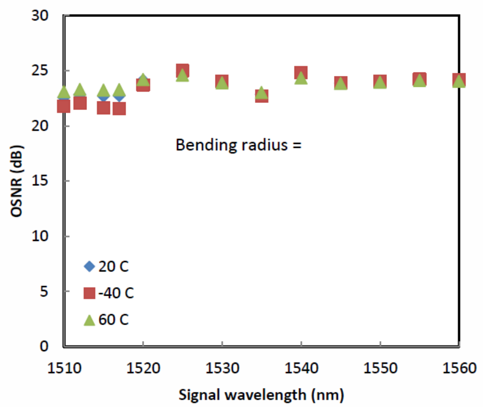

Fig. 6. The optical signal to noise ratio (OSNR) as a function of signal wavelength with the macro-bending effect for different values of temperature (-40, +20 and +60 ^{0}C). At input signal and pump power, -30 dBm and 100 mW, respectively

From Fig. 6, in the range (1510- 1520 nm) OSNA increases with temperature and in the range (1525 – 1560 nm) decreases with temperature increase, therefore the optical signal in this range have higher gain with the increasing temperatures.

Fig. 7 and Fig. 8 show spectral changes of the gain and noise figure as a function of the input signal wavelength for EDFA with and without macro-bending, at different values of temperature (-40, 20 and 60 ^{0}C) for amplifier length 15 m and bending radius 4mm . The input signal power -30 dBm and pump power 100mW. As shown in Fig. 7, for the normal case (without bending), as the temperature increases, the gain of EDFA increases for all values of signal wavelength. Also for the bending case, the gain of EDFA increases for all values of signal wavelength. From Fig. 7, the gain is higher of ~ 5 dB when the temperature increases from -40 to 60 C with macro-bending at a wavelength 1540 nm. Fig. 8 shows, noise figure reduction for bending case rather than without bending effect, the noise figure of the EDFA at wavelength 1540 nm is reduced by ~ 0.44 dB for temperature changes from -40 to 60 ^{0}C for macro- bending case of EDFA.

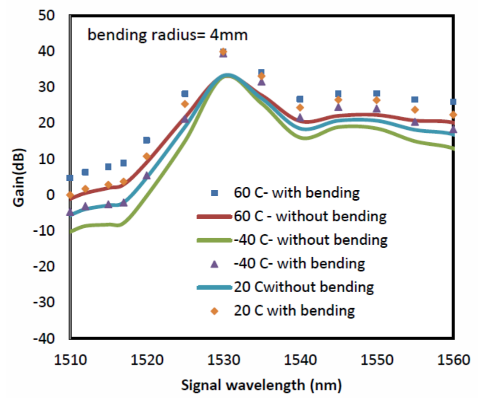

Fig. 7. Gain profile as a function of signal wavelength for EDFAwith and without the bending effect, for different values of temperature (-40, +20 and +60 ^{0}C). At input signal and pump power, -30 dBm and 100 mW, respectively

Fig. 9 and Fig. 10 show the variations of the gain and noise figure as a function of an input pump power of EDFA with macro-bending for amplifier length 15 m and bending radius 4 mm at signal wavelength 1530 nm and signal power -30 dBm at temperatures(-40, 20 and 60 ^{0}C). As the temperature increases, the gain decreases for the input pump power variations and the gain increases with the input power increases at the temperatures (-40, 20 and 60 ^{0}C).

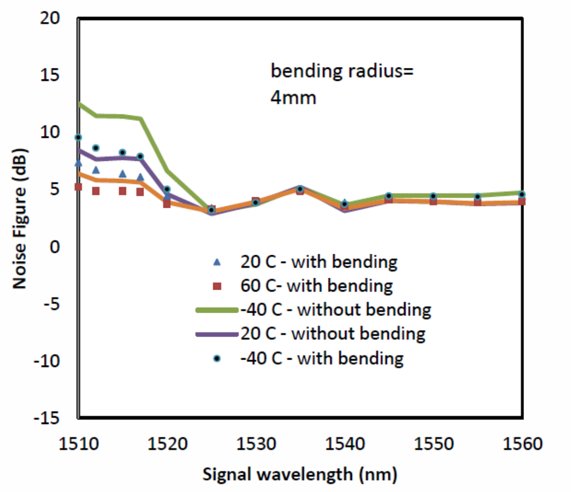

Fig. 8. Noise figure profile as a function of signal wavelength for EDFAwith and without the bending effect, for different values of temperature (-40, +20 and +60 ^{0}C). At input signal and pump power, -30 dBm and 100 mW, respectively

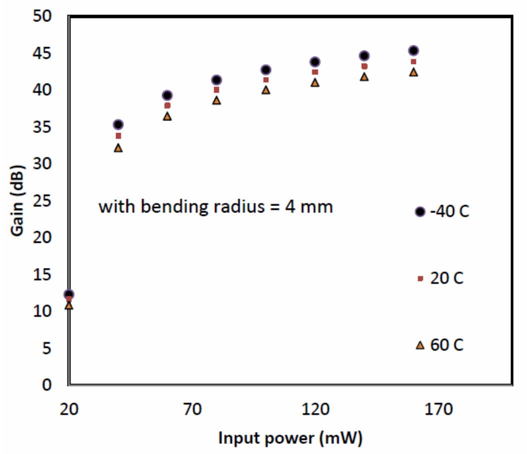

Fig. 9. Gain of macro-bending effect EDFA for different values of temperature (-40, +20 and +60 ^{0}C) as a function of pump power, at input signal and pump power, -30 dBm and 100 mW, respectively

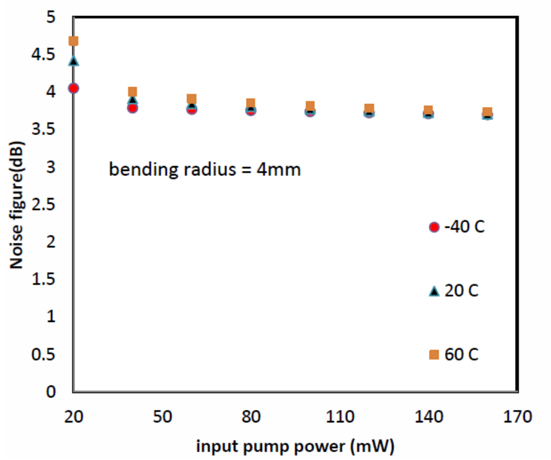

Fig. 10. Noise figure of macro-bending effect EDFA for different values of temperature (-40, +20 and +60 ^{0}C) as a function of pump power, at input signal and pump power, -30 dBm and 100 mW, respectively

On the other hand, the noise figure increases with temperature increases for macro-bending EDFA at the input power (20 – 170 mW), and the noise figure decreases with input pump power increase at temperatures (-40, 20 and 60 ^{0}C).

4. Conclusion

We purposed the study of the dependence of the gain and noise figure of macro-bending EDFA on temperature in this paper. Where the dependence of the gain and noise figure on macro-bending effect also have been calculated in the wavelength region 1510- 1560 nm, for fiber bending radius 4mm and amplifier length 5- 35 m, with input signal power -30 dBm and input pump power (20 – 170 mW). We obtained improvements for both gain and reduction of noise figure for macro-bending case than normal case (without macro-bending EDFA) as obtained before by S. A. Daud et al., and our studies of temperature show a dependence of macro-being EDFA on the temperature, so we can obtain another improvement for gain and reduction of noise figure with temperature changes. The macro-bending action is to decrease the ASE and increase the gain. From our study we concluded, as an example, that the gain is higher of ~ 5 dB when the temperature increases from -40 to 60 C with macro-bending at a wavelength 1540 nm, and the noise figure reduces at wavelength 1540 nm by ~ 0.44 dB for temperature changes from -40 to 60 ^{0}C for macro- bending case of EDFA.

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