Gain and noise figure optimization of a macrobending EDFA/Er^{3+}-Yb^{3+} Co-doped hybrid optical amplifier

O.MAHRAN[a,b,*], MOUSTAFA H. ALY[c]

[a]*Faculty of Science, Physics Department, Alexandria University, Mohram Bey 21511, Alexandria, Egypt,*

[b]*Faculty of Science, Physics Department, Al Jouf University, Al Jouf, Saudi Arabia.*

[c]*College of Engineering and Technology, Electronics and Communications Engineering Department, Arab Academy for Science, Technology and Maritime Transport Alexandria, Egypt, Member of OSA.*

In this paper, the gain and noise figure are experimentally studied and investigated for a hybrid amplifier system (HAS) containing a macrobent EDFA as a pre-amplifier in cascade with Er/Yb co-doped amplifier (EYCDFA) as a post-amplifier. The hybrid system is performed under a dual forward pump configuration at 980 nm. The EDFA bending radius is chosen as 4 mm. The affecting parameters to be optimized are the EDFA and EYCDFA pump powers, input signal power, signal wavelength, EDFA and EYCDFA lengths. The macrobent HAS performance is compared with normal HAS with a straight EDFA (without bending) and the other experimental data of recent works showing an improvement in both gain and noise figure. The gain of bent HAS is increased to 68.67 dB and the noise figure is decreased to 4.6 dB, where the corresponding values of the normal HAS are respectively, 64.3 dB and 4.78 dB, at optimized parameters of 15 m EDFA length, 1 m EYCDF length, 500 mW EDFA pump, 100 mW EYCDFA pump and - 40 dBm input signal power at 1530 nm.

(Received February 24, 2016;

Keyword: Macrobending- EDFA- Hybrid optical amplifier – EYCDA

1. Introduction

The technology of signal transmission and optical networks, which allows transmission of multi-gigabits through large distances in optical fibers needs a high gain and low noise optical amplifiers to overcome the attenuation and dispersion during propagation [1,2]. Erbium doped fiber amplifier (EDFA) was considered as the best amplifier that solves most of difficulties in signal transmission due to the ability of providing large gain, low noise and board-band amplification in the C- band (1530 nm - 1570 nm) [3-5].

Literature reported the characteristics of EDFA and the methods to improve these characteristics. IJiuru Yang et al. used a fiber Bragg grating to improve the EDFA gain flatness and stability was obtained by suitable gain-clamping [6]. Furthermore, many researches are directed to short length, co-doped fiber amplifiers like erbium-ytterbium (Er/Yb) co-doped fiber amplifier for achieving high gain with large bandwidth and low cost components of optical networks [7, 8]. In the Er/Yb co-doped fiber amplifier, the presence of Yb ions reduces the up-conversion rate of the higher level of Er and provides high gain and low noise. When compared with EDFA, Er/Yb doped fiber lasers and amplifiers show a growing potential for many applications in different areas such as industry, medicine, communications, military and research [9]. S.H. Xu et al. measured gain and noise figure of single mode highly Er/Yb co-doped phosphate with a dual pump configuration at different values of input signal power [10]. They obtained a net gain coefficient as high as 3.3 dB/cm from an EDFA based on a 5 cm long phosphate fiber [10].

The effect of macrobending fiber amplifier shows a suppression of amplified spontaneous emission (ASE) and reduces noise to a low level, which achieves a high gain as compared to the gain of normal case (without bending) [11]. The macrobending gain characteristics and noise figure of thulium doped fiber amplifier are studied in [12]. It was shown that band pass filtering the optical signal using macrobending leads to suppressing the ASE at 800 nm and 1800 nm wavelength region and thus improves both gain and noise figure performance [12]. In another research [13], EDFA gain and noise figure were improved using the macrobending effect and 12-14 dB gain enhancements are obtained at 1525 nm with low noise figure [13].

The hybrid amplifiers are a combination of two or more amplifiers in cascade as a pre-amplifier and a post-amplifier to improve the performance characteristics of the amplifier due to introducing more parameters on which the performance depends as well as a varity of optical pump configurations and amplifier types. Z. G. Lu et al. purposed a high power and extremely high gain hybrid fiber amplifier with a suitable noise figure (NF) performance. It comprises a two-stage EDFA as a pre-amplifier and an Er/Yb co-doped double-cladding fiber amplifier as a post-amplifier. In their work at the signal wavelength of 1550 nm, the signal gains up to 70 dB and a maximum output power of 36.9 dBm when the total pump power is 12.5 W [14-18].

In the present, we improve the characteristics of the optical amplifier, through hybrid connection by choosing the optimum parameters on which the performance of hybrid amplifier depends on for achieving high gain and low noise. For the sake of this objective, we purpose a hybrid amplifier system (HAS) that contains a bent EDFA as a pre-amplifier in cascade with Er/Yb co-doped amplifier (EYCDFA), a short length amplifier, as a post-amplifier (bent HAS) and a normal EDFA (without bending) hybrid with EYCDA (normal HAS). The bend-loss coefficient is chosen corresponding to a bending radius of 4 mm.

The experiment is carried out two times; one for normal HAS and the other for macrobent HAS. The input parameters are: EDFA pump power 100-500 mW with forward configuration at 980 nm, EYCDFA is forward pumped with 100-500 mW, EDFA length is 10 - 35 m, EYCDFA length is 0.3-1.2 m and input signal in the C-band with power of - 40 to 20 dBm. The bent HAS gain and noise figure are compared to gain and noise figure of normal HAS and are also compared to the data of Refs. [13, 14] showing a fair agreement.

2. Bent fiber

The coefficient of bending loss, α_b, in single mode fibers with step index profiles was developed by Marcuse, where the total loss of a macro-bent fiber is [19]

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

where a is the fiber core radius, $K_{\nu-1}(\gamma a)$ and $K_{\nu+1}(\gamma a)$ are the modified Bessel functions [19], $k_1 = [n_c^2 k^2 - \beta^2]^{1/2}$, $k = 2\pi/\lambda$ is the wave number, $\beta = n_{cl} k[1 + b\Delta]$ is the propagation constant of the fundamental mode, $\gamma = [\beta^2 - n_{cl}^2 k^2]^{1/2}$, $V = ak[n_c^2 - n_{cl}^2]^{1/2}$ is the normalized frequency, $\Delta = [n_c^2 - n_{cl}^2]/2n_c^2$, n_c and n_{cl} are the core and cladding refractive indices, b is the fraction of the total electric field of the fundamental mode in the core [10-14].

R_{eff} is the effective bending radius, which is related to the fiber bending radius by

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

where P_{11}(typically = 0.12) and P_{12} (typically = 0.27) are the elasto-optical tensor components and ν is Poisson's ratio (typically = 0.17) for the fiber material [20, 21].

The stress bent fiber refractive index, n_b, is given by [19]

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

with x the position on the bending direction.

The physical refractive index of the fiber changes with fiber bending. The stress-optical effect yields a material refractive index distribution of the form [19]

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

where n is the refractive index of the straight fiber.

For silica fibers, $R_{eff}/R = 1.28$ [19].

3. Experiment setup

Fig. 1 shows the HAS for macrobending and normal case (without bending) experimental setup, designed by Opti-system ver.13. The system setup consists of 70 channels covering the wavelength range 1520-1590 nm.

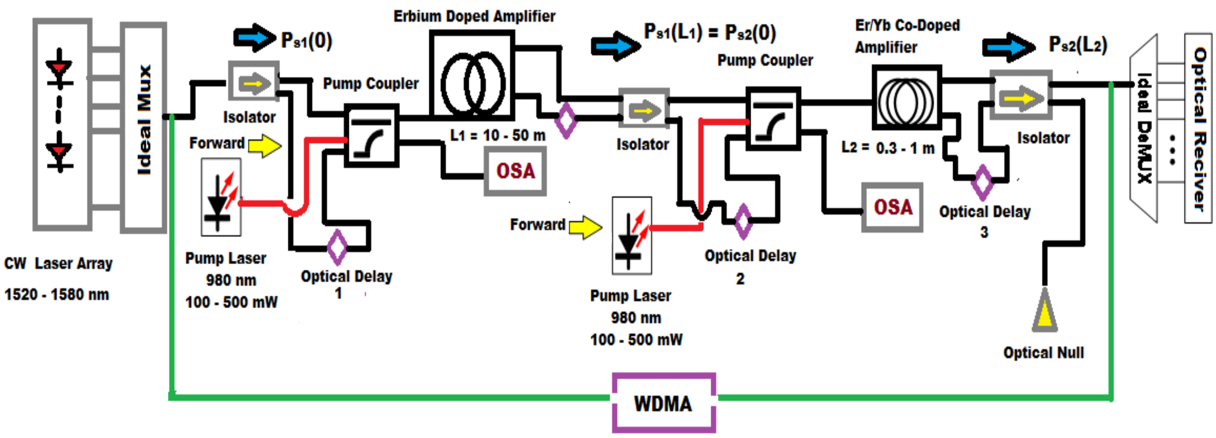


Fig.1. Hybrid macrobent EDFA/EYCDFA experimental set-up.

For the macrobent HAS, the optical loss coefficient of erbium doped fiber (EDF) is calculated for different values of signal wavelength according to Eqs. (1-4), as displayed in Fig.2. The values of the parameters used in calculations are found in Table 1.

Table 1. Parameters of the bending loss calculations.

Symbol	Definition	Value
a	core radius	1.346 μm
b	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

The values of optical loss coefficient corresponding to a bending radius, R, of 4 mm are inserted in the simulation experiment. The experiment is performed using a continuous wave (CW) laser array. The input signal $P_{s1}(0)$ is directed to the isolator and is coupled with the EDFA input pump power through the pump coupler. The 980 nm pump laser of 100 to 500 mW is used for EDFA in the forward direction, with the optical signal analyzer (OSA) for measuring the pump power which is directed to EDFA. An erbium doped alumina-silicate glass fiber was chosen at lengths of L_1 = 10-35 m. The output signal $P_{s1}(L_1)$ of EDFA which is considered as input signal for the second amplifier $P_{s2}(0) = P_{s1}(L_1)$ is directed from the isolator and is coupled with the input pump power of EYCDFA through the pump coupler. Also, a forward 980 nm pump laser of 100 to 500 mW is used for EYCDFA, with the OSA for measuring the pump power directed to EYCDFA of length L_2 = 0.3-1 m. The output signals $P_{s2}(L_2)$ are demultiplexed by fiber Bragg gratings and are recorded by the optical receiver.

4. Results and discussion

Fig. 3 shows the gain and noise figure as a function of signal wavelength for the bent and normal HAS, respectively, at the assigned parameters values. It is clear that, both gain and noise figure are higher in the bent HAS at most of signal wavelength range except at some wavelengths, where the noise of normal case is much higher. The highest value of the gain (68.67 dB) and the lowest value of the noise figure (4.62 dB) for macrobending case occur at 1530 nm, corresponding to 61.64 gain and 5.15 noise figure for the normal HAS. This difference is due to suppressing the amplified spontaneous emission (ASE) in the case of macrobent HAS.

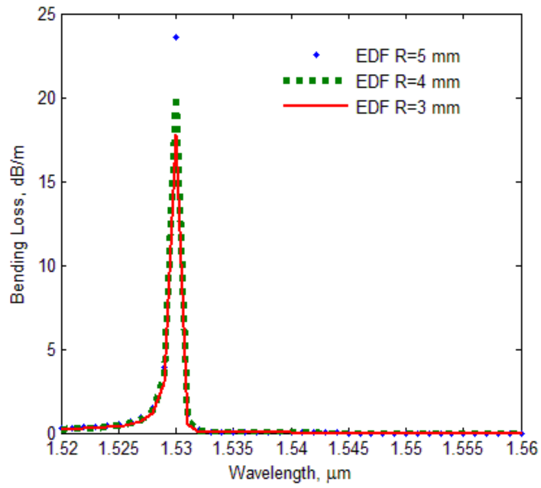


Fig.2 EDF bending-loss coefficient against wavelength for different bending radii 3, 4 and 5 mm.

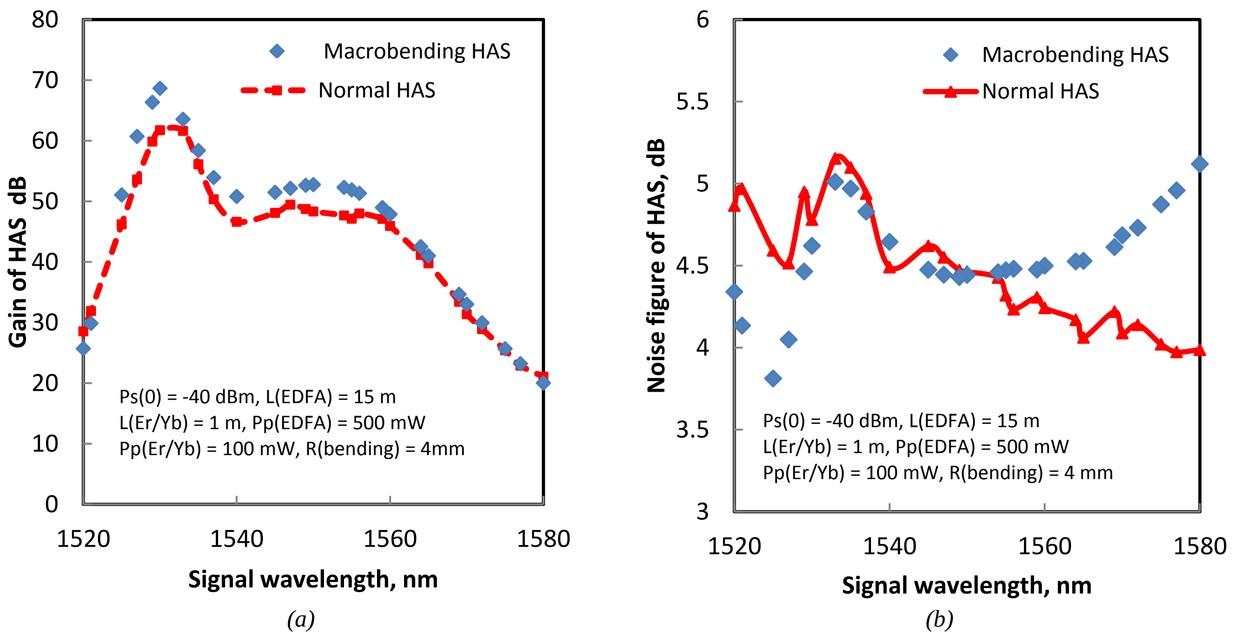
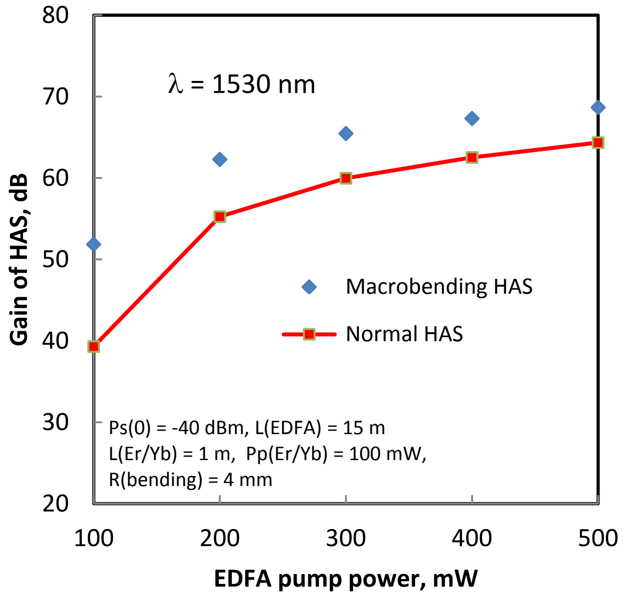
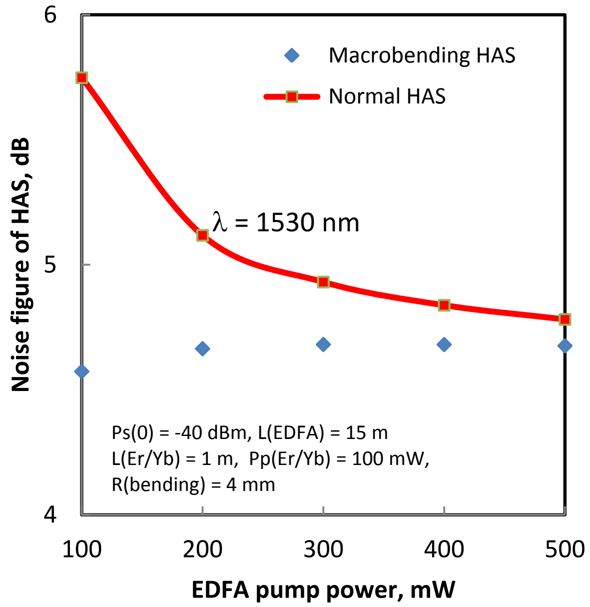


Fig.3 HAS gain and noise figure as a function of signal wavelength for bent and normal cases.

The effect of EDFA pump power on both gain and noise figure is depicted in Fig. 4, at 1530 nm for both macrobent and normal HAS. For the two systems, bent and normal cases, gain increases with EDFA pump power. Furthermore, the rate of increase in gain is in the range of pump power 100 - 200 mW, then a less rate of increase in the range 300 - 500 mW. The highest gain value obtained for the bent HAS is 68.67 dB at EDFA pump power 500 mW. From Fig. 4, it is also noted that noise figure decreases with the pump power in normal HAS and is nearly constant for the bent HAS. The values of noise figure for the bent HAS is lower than that of the normal case. The lowest value of noise figure is 4.6 dB at EDFA pump power of 500 mW which is obtained for the bent HAS.

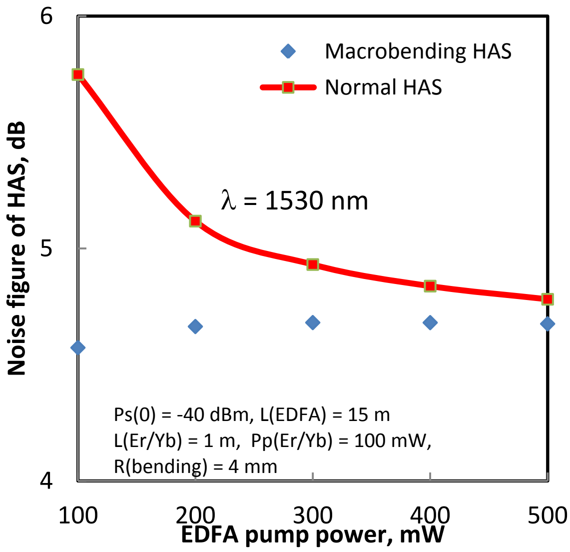


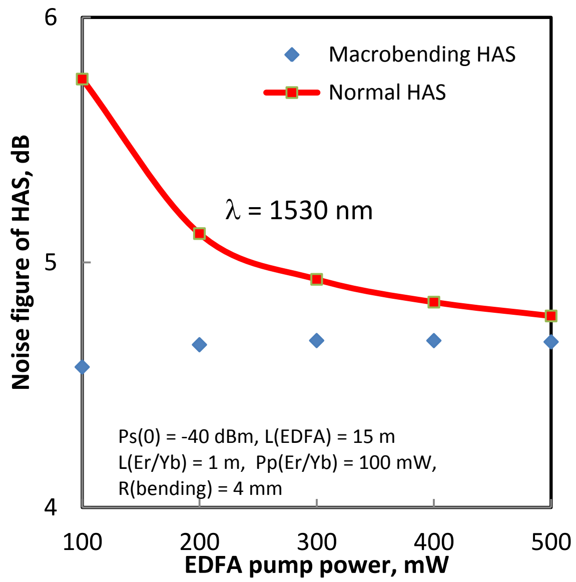


(a) *(b)*

Fig.4 HAS gain and noise figure as a function of EDFA pump power for bent and normal cases.

The dependence of the gain and noise figure on the Er/Yb pump power for both bent and normal systems is represented in Fig.5 (a) and (b), respectively, at signal wavelength of 1530 nm, input signal power of - 40 dBm, EDFA pump power of 100 mW, EDFA length of 15 m and Er/Yb co-doped length of 1 m. The behavior of the gain with Er/Yb pump power is similar to that of Fig.4 (a) except that the highest value of the gain is 61.98 dB at 500 mW for the bent HAS which is smaller than that obtained at the same value of EDFA pump power. Noise figure has almost constant behavior with Er/Yb pump power variation for HAS cases and the lowest value of noise is 4.56 dB at 500 mW of Er/Yb pump power obtained in case of bent HAS. Generally, one can say that, macrobending improves the performance of both gain and noise figure of the proposed (bent) HAS.

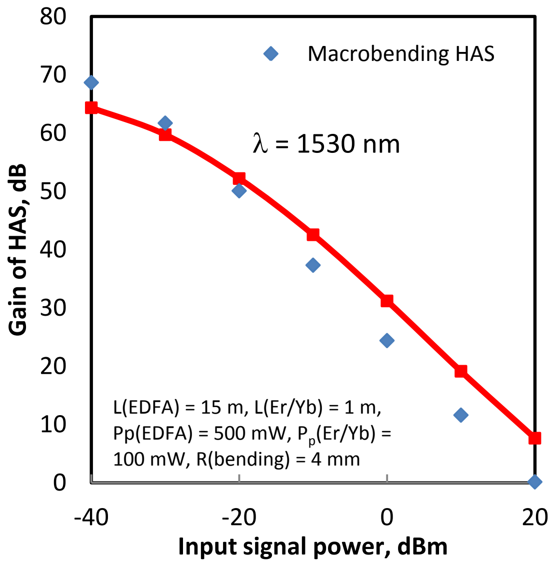




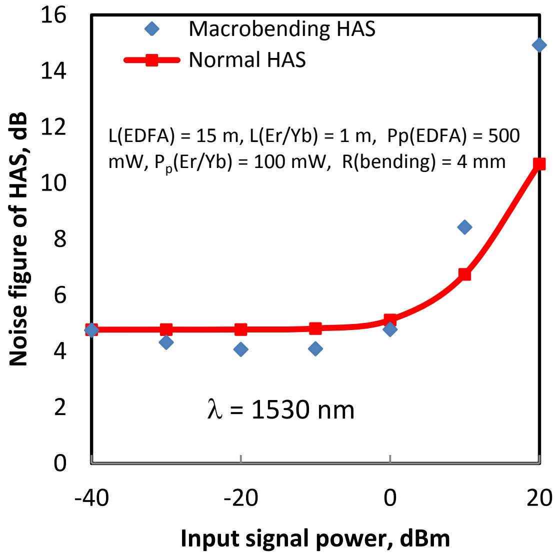
(a) *(b)*

Fig.5 HAS (a) gain and (b) noise figure as a function of of Er/Yb co-doped pump power for bent and normal cases.

Fig. 6 displays gain (a) and noise figure (b) of HAS versus input signal power in the range -40 to 20 dBm for both bent and normal cases at 1530 nm. The experiment is performed at EYCDFA and EDFA pump powers of 100 mW, 500 mW, respectively, EYCDFA and EDFA lengths of 1 m, 15 m, respectively. It is clear that for both bent and normal cases, gain decreases and noise figure increases with input signal power. From Fig. 6(a), till - 30 dBm signal power, the gain of bent HAS is higher than that of normal HAS. After that, the normal HAS gain becomes larger than that of bent HAS. Therefore, the best values of input signal power for maximum gain in both HAS types are between (-30 to -40 dBm). The highest value of the gain (68.67 dB) occurs at - 40 dBm. Furthermore, Fig. 6(b) shows an increase in noise figure of the bent HAS over that of normal HAS for values of signal power > 0 dBm.



(a)

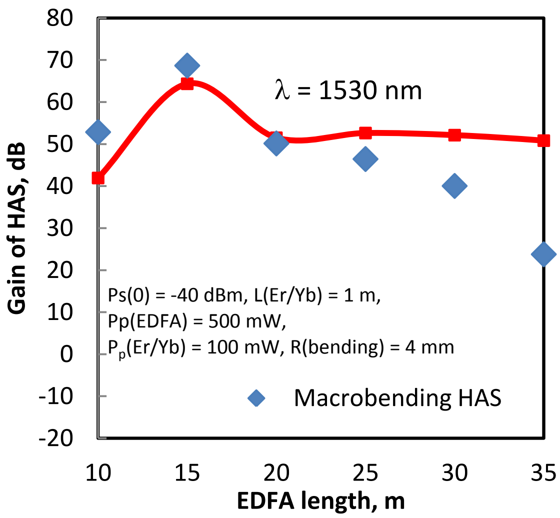


(b)

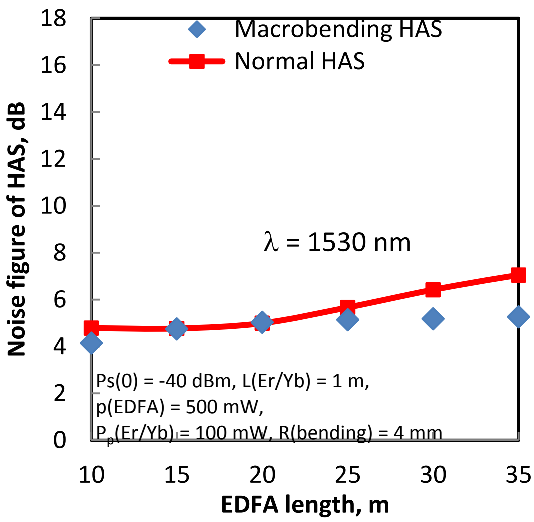
Fig.6. HAS (a) gain and (b) noise figure as function of input signal power for bent and normal cases.

In this study, the length of both amplifiers, the pre-amplifier (bent EDFA) and the post-amplifier (EYCDFA) must be adjusted as well as the other parameters to give the best gain and noise figure performance of the proposed hybrid system. This is clearly illustrated as follows.

Fig. 7 displays (a) gain and (b) noise figure versus the EDFA length in the range 10 to 35 m (short length) for bent and normal cases at 1530 nm. The experiment is performed at 100 mW pump power of EYCDFA, 500 mW pump power of EDFA, - 40 dBm input signal power and EYCDFA length of 1m. The gain has its maximum value at 15 m length of EDFA for both macrobent HAS (68.67 dB) and normal HAS (64.3 dB). The HAS gain decreases as the length of EDFA is higher than 15 m for bent HAS and is nearly constant for normal HAS. Noise figure shows a slightly increasing behavior with the EDFA length and the values of noise figure of macrobent HAS are smaller than that of normal case for EDFA length > 25 m. The lowest value (4.1 dB) of noise figure occurs at 10 m length of EDFA for the bent HAS.



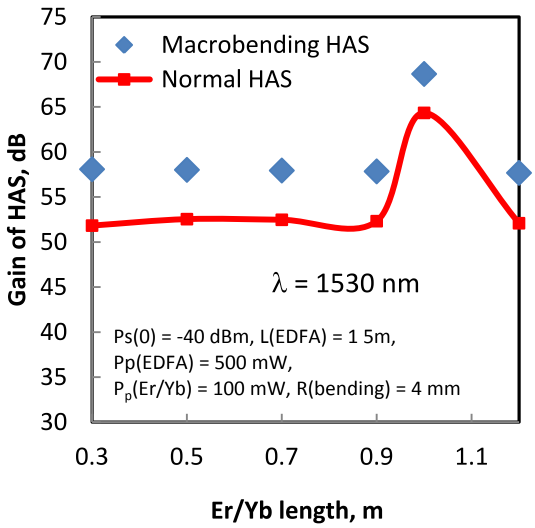
(a)



(b)

Fig.7 HAS (a) gain and (b) noise figure as function of EDFA length for bent and normal cases.

In a similar way, the effect of EYCDFA length (short length) is investigated in Fig. 8 for both cases, at 1530 nm, - 40 dBm input signal, 100 mW EYCDFA pump power, 500 mW EDFA pump power, and 15 m length. Obviously, when compared with the normal HAS, the bent HAS gain is higher, while noise figure is lower. As EYCDFA length increases the gain is nearly constant around the value of 58 dB except at 1 m, where gain becomes maximum at the value of 68.67 dB for the bent system. The same behavior of the gain occurs for the normal HAS around 64.3 dB except at 1 m, where gain becomes maximum at the value of 64.3 dB. Fig. 8(b) indicates a weak increase in noise figure with EYCDFA length for cases and its lowest value (~4 dB) occurs at 0.3 m of EYCDFA for the bent HAS.



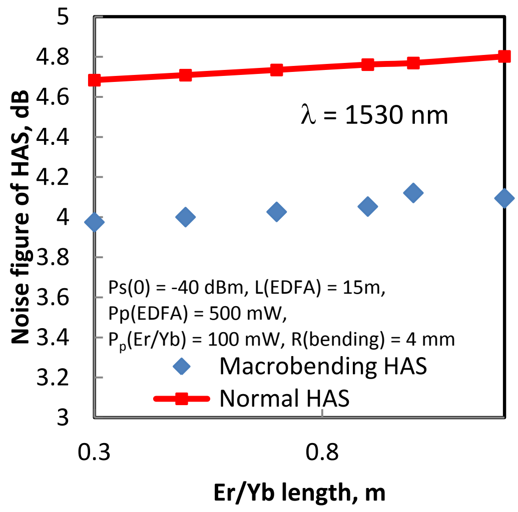
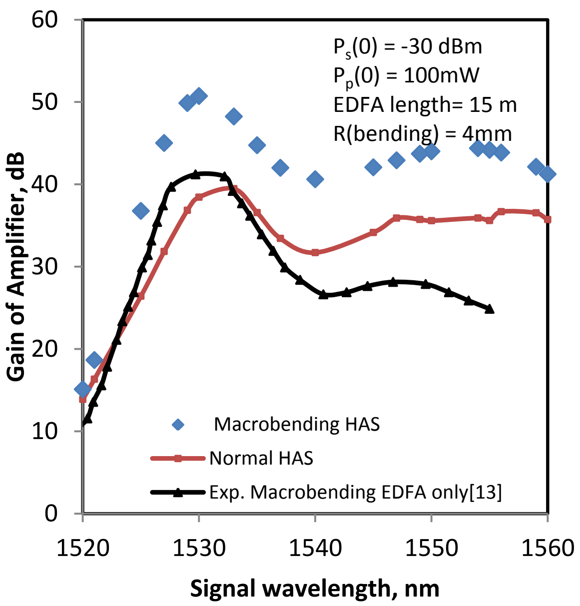


Fig.8. HAS (a) gain and (b) noise figure as functions of Er/Yb co-doped length for bent and normal cases.

5. Comparison

For the sake of evaluation of our work, a comparison is carried out between the obtained results and that obtained in Refs. [13, 14]. In Fig.9, we performed our experiment for macrobent HAS and normal HAS at 100 mW pump power of both EDFA and EYCDFA, and at -30 dBm input signal power, 15 m EDFA and 1 m EYCDFA to compare our results with the results of Ref. [13] for (a) gain and (b) noise figure as functions of signal wavelength. It is clear that our bent HAS gives a higher gain and a lower noise figure in comparison with the corresponding values of macrobending EDFA only of Ref. [13].



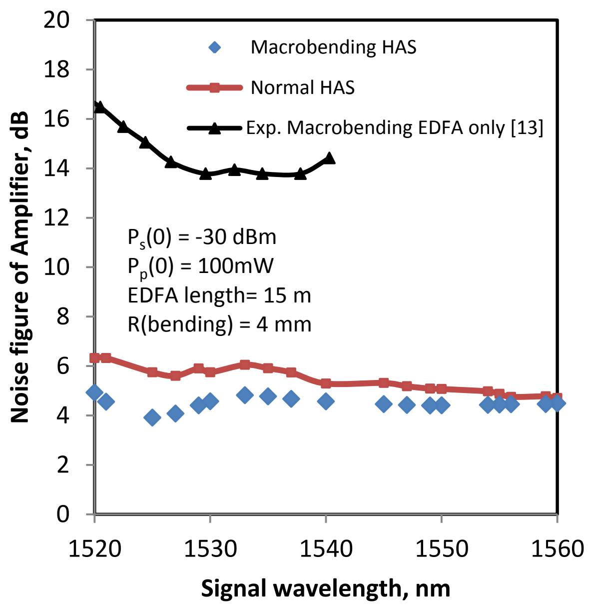
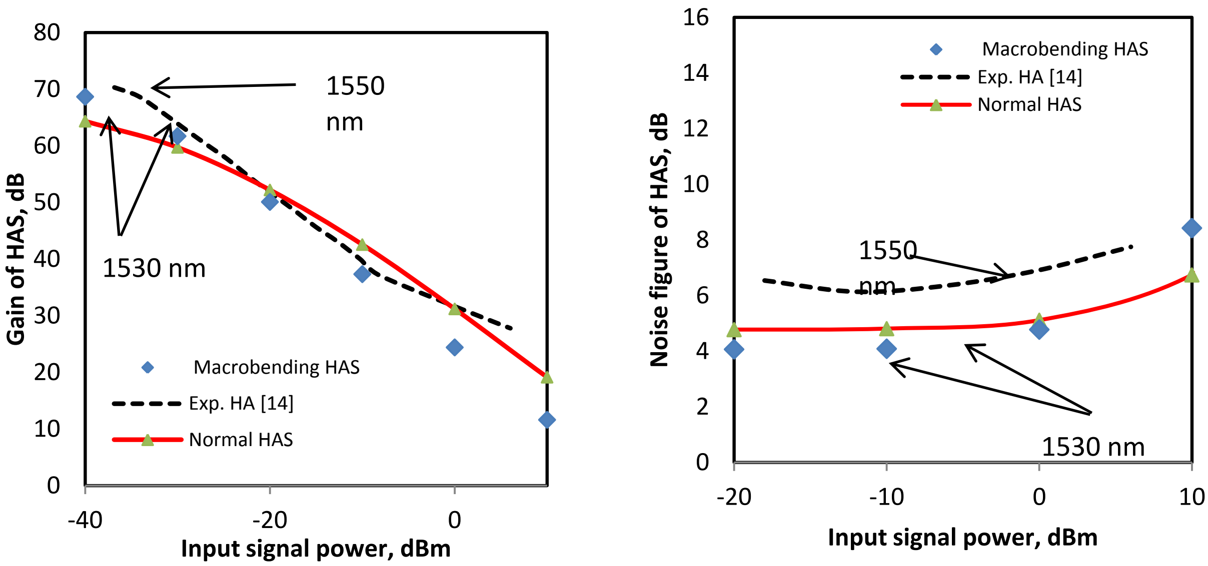


Fig.9. HAS performance comparison (a) gain and (b) noise figure as functions of signal wavelength for macrobending EDFA only [13] with our macrobent and normal cases.

To prove the technical challenge of our system which offers high gain and low noise figure with short length amplifiers of EDFA and EYCDFA and low pump power ~ 0.6 W with lowest cost components, we compare also with another hybrid amplifier [14] comprising a two-stage EDFA (of lengths 6 m + 26 m) as the pre-amplifier part and an EYCDFA (of length 13.8 m) as the post-amplifier part with total pump power of 12.5 W at 1550 nm, as shown in Fig.10. The input signal is - 37 dBm, , EYCDFA and EDFA pump powers are, respectively, 100 and 500 mW, with lengths of 15 m and 1 m for the macrobent HAS and normal HAS at 1530 nm. A fair agreement is shown in Fig. 10.



(a) *(b)*

Fig.10. HAS performance comparison (a) gain and (b) noise figure as functions of input signal power for hybrid amplifier [14] with our macrobent and normal cases.

The comparison between the obtained results of the proposed HAS and the corresponding experimental values of Refs. [13 and 14] are summarized in Tables 2 and 3.

Table 2. HAS compared to macrobending EDFA of S.D. Emami et al. [13].

Amplifier	Gain(dB)	Noise figure(dB)
Macrobent HAS	50.72	4.57
Normal HAS	38.43	5.7
Macrobending EDFA [13]	41.4	13.9

Table 3. HAS compared to the hybrid amplifier (HA) of Z. G. Lu et al. [14].

Amplifier	Gain(dB)	Noise figure(dB)
Macrobent HAS at 1530 nm	68	4.74
Normal HAS at 1530 nm	63.34	5
HA [14] at 1550 nm	70.3	< 6

6. Conclusion

We purposed a new hybrid amplifier system comprising a two-stage macrobent EDFA and or /normal (without bending) EDFA as a pre-amplifier and an EYCDFA as a post-amplifier to obtained a high performance with higher gain and lower noise figure. This is essential in most applications of optical networks, wavelength division multiplexing systems, industry, communications, military and research. The characteristics of the optical hybrid amplifier are improved by choosing optimum values for the affecting parameters. These are: the EDFA pump power with a forward configuration at 980 nm, EYCDFA forward pump configuration, EDFA and EYCDFA lengths and input signal power at C- band. From the experiment, the highest gain was obtained for the bent HAS with a value of 68.67 dB as well as the lowest noise figure of 4.6 dB when compared to normal HAS (gain of 64.3 dB and noise 4.78 dB). The optimized values of the affecting parameters are: 15 m EDFA length, 1 m EYCDF length, 500 mW and 100 mW EDFA and EYCDFA pump power, respectively, and - 40 dBm input signal power at 1530 nm. The obtained results have shown an improvement in both gain and noise figure when compared with the published work in Refs. [13 and 14] with shorter amplifier lengths and lower pump power.

References

[1] E. Desurvire, Erbium Doped Fiber Amplifiers: Principles and Applications, Wiley, New York, 1994.

[2] O. Mahran, Ahmed E. El-Samahy, Mohammed Salah Helmy, Mourad Abd El Hai, Optoelectron. Adv. Mat. **4**(12), 1994 (2010).

[3] M.A. Mahdi, F.R. Mahamd Adikan, P. Poopalan, S. Selvakennedy, W.Y. Chan, H. Ahmad, Optics Communications, **176**, 125 (2000).
[4] H.B. Choia, J.M. Oha, D. Leea, S.J. Ahnb, B.S. Parkc, S.B. Leed, Optics Communications, **213**, 63 (2002).
[5] H. Hsu, Y.Yu, S.Liaw, R.Liu, C.Shin, Opt. Laser Technol., **56**, 307 (2014).
[6] Jiuru Yang, Xiangyu Meng, Chunyu Liu, Opt. and Laser Technol. **78**, 74 (2016).
[7] J. Nilson, P. Scheer, B. Jaskorzynska, IEEE Photon. Technol. Lett., **6**(3), 73 (1994).
[6] F. Di Pasquale, M. Federighi, IEEE J. Quantum Electron., **30**(9), 2127 (1994).
[7] L. Goldberg, J. Koplow Electronics Letters, **34(**21), 2027 (1998).
[8] S.H. Xu, Z.M. Yang, Z.M. Feng, Q.Y. Zhang, Z.H. Jiang, W.C. Xu, Proceeding of 2nd IEEE International Conference on Nanoelectronics, Shanghai, China, p. 633, 2008.
[9] Alun J. Harris, Paul A. Shrubshall, Peter F. Castle, J. Lightwave Technol., **LT-4**(1), 80 (1986).
[10] S. D. Emami, H. A. Abdul-Rashid, S. Z. M. Yasin, K. A. M. Shariff , S. E. Mirnia, A. Parvizi, H. Ahmad, S. W. Harun, Appl. Phys. B, **108**, 807 (2012).
[11] S. A. Daud, S. D. Emami, K. S. Mohamed, N. M. Yusoff, L. Aminudin, H. A. Abdul-Rashid, S. W. Harun, H. Ahmad, M. R. Mokhta, Z. Yusoff, F. A. Rahman, Laser Physics, **18**(11), 1362 (2008).
[12] Z.G. Lu, J.R. Liu, F.G. Sun, G.Z. Xiao, P. Lin, Optics Communications, **256**, 352 (2005).
[13] O. Mahran, Australian J. Basic & Appl. Science, **9**(11), 84 (2015).
[14] O. Mahran, Ahmed E. El-Samahy, Moustafa H. Aly, Mourad Abd EL Hai, Optoelectron. Adv. Mat. 9(5-6), 575 (2015).
[15] O. Mahran, Moustafa H. Aly, Appl. Optics, **55**(1), 22 (2016).
[16] O. Mahran, Optical Materials, **52**, 100 (2016).
[17] O. Mahran, Optics Communications, **353**, 158 (2015).
[18] D. Marcuse, Appl. Opt. **21**, 4208 (1982).
[19] Alexander C. Thompson, Peter J. Cadusch, David F. Robertson, Paul R. Stoddart, Scott A. Wade, J. Lightwave Tech., **30**(22), 3500 (2011).

*Corresponding author: o_mahran2003@yahoo.com