The effect of concentration of Er^{3+} and Yb^{3+} on 28.5 dBm pump power Er^{+3}/Yb^{+3} Co-Doped / Raman Hybrid Amplifier (HA)

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We present analytically the effect of concentration of Er^{3+} and Yb^{3+} on the gain and noise figure characteristics of Er-Yb co-doped/Raman hybrid amplifier (HA) at pump power of 28.5 dBm . The gain and noise figure are calculated at steady state conditions, neglecting ASE with 1m length of Er-Yb co-doped, 25 km Raman amplifier length and input signal power of -40 dBm in the signal wavelength range (1525 – 1610 nm). The maximum gain (53.92 dB at 1530 nm and 43.8 dB at 1600 nm) and minimum noise figure (3.48 dB at 1530 nm and 5.65 dB at 1600 nm) are obtained for the hybrid amplifier at 5.14×10^{25} m^{-3} Er concentration and 1×10^{26} m^{-3} Yb concentration , on the other hand the gain shows large values at end range of signal wavelength with the same input parameters listed above due to hybrid Raman amplifier with EYDFA so, a flat gain is observed in the all range of signal wavelength with higher band width.

(Received February 24, 2016; accepted April 05, 2016)

Keywords: EYDFA, Signal power, Raman, Hybrid amplifiers, Signal wavelength

1. Introduction

From many years, many reports dealing the fiber design has been introduced using rare earth-doped fiber for amplifications the optical signal of low power due to transmission in long distance fibers and laser applications [1], the most importance of these reports which working with glasses doped with rare-earth ions like erbium, ytterbium, Thulium and so on. [2]. Due to high rate speed and voice/data transmission capacity it became necessary to use additional dopants and co-dopants for increasing the bandwidth of the communications. Erbium-ytterbium (Er^{3+}/Yb^{3+}) doped fiber lasers and amplifiers are suggested for this purpose and for many applications in different areas such as industry, medicine, communication, military and research.

Work on modeling of Er3+/Yb3+ co-doped CW fiber amplifiers and lasers has been performed in the last years [3]. These models have proved to be accurate for understanding the optical amplifier or laser behavior [4].

The optical amplifiers using Er_/Yb doped phosphate glass have been received important interests due to the high gain as well as potential low cost for a large number of applications such as optical communications at standard wavelengths 1530–1560 nm, metrology, and telemetry at eye-safe wavelengths[5], free-space communications, long wavelength L-band amplifiers, short-active-length integrated amplifiers [6], and super-fluorescent sources. While the first Er_Yb fiber amplifiers were pumped in the core at a wavelength of 1.06 µm, more recently, cladding pumping in the 920 to 980 nm absorption band of Yb has been used [7]. Also erbium-ytterbium (Er^{3+}/Yb^{3+}) doped fiber lasers and amplifiers show a growing potential for many applications in different areas such as industry, medicine, communication, military and research. Cladding pumped fiber lasers based on Er^{3+}/Yb^{3+} doped silicate glass are an attractive technology for compact and efficient sources in the eye-safe spectral range [8], for both high power continuous wave (CW), as well as high repetition rate and high energy short pulse generation.

The hybrid amplifiers which are combinations of Raman and EDFA has been demonstrated for many applications like, higher transmission capacity on DWDM systems, because the non-linear gain spectrum of Raman amplifier in conjunction with saturation effects of EDFAs cause increase in signal power and decrease the optical signal- to- noise ratio [9-11].

In this paper we study the effect of concentration of Er^{3+} and Yb^{3+} on the gain and noise figure of hybrid amplifier, which is a combination of two amplifier, Er/ Yb co-doped amplifier of length 1m and Raman amplifier of length 25 km, with dual pumps are used, one forward at 980 nm with power of 500 mW for Er/Yb co-doped and the other pump is backward at 1450 nm with power of 200 mW for Raman amplifier so the total pump power is 700 mW ≈ 28.5 dBm at input signal of -40 dBm at signal wavelength of (1525 – 1610 nm). The hybrid amplifier is purposed for improving the gain and noise figure of the optical amplifier.

The host glass used is phosphate, phosphate glasses have their unique characteristics that include high transparency, low melting point, high thermal stability, high gain density that is due to high solubility for lanthanide (Ln) ions, low refractive index and low dispersion , the most applications of such hybrid are i- high transmission capacity DWDM, ii- common antenna television (CATV), iii- free space communications and iv- long wavelength L- C band amplifier[12].

2. Theory

Supposing in fig. 1, N_1, N_2 and N_3 are the Er^{3+} ion concentrations on the $^4I_{15/2}$, $^4I_{13/2}$ and $^4I_{11/2}$ levels, respectively; N_{Er} is the total Er^{3+} ion concentration; N_4 and N_5 are the Yb^{3+} ion concentrations on the $^2F_{7/2}$ and $^2F_{5/2}$ levels, respectively; N_{Yb} is the total Yb^{3+} ion concentration. Under the conditions of the uniform dopant and the steady-state, the Er^{3+} ion and Yb^{3+} ion on the corresponding levels depend on the amplifier length z, i.e., $N_i = N_i(z)$. Therefore, the multilevel rate equations for the Er^{3+}-Yb^{3+} co-doped system under uniform dopant and steady- state conditions, can be written as [13]

$$\frac{\sigma_{12}(\nu_s)P_s(z)\Gamma_s N_1(z)}{A_c h\nu_s} + \frac{\sigma_{13}(\nu_p)P_p(z)\Gamma_p N_1(z)}{A_c h\nu_p} - \frac{\sigma_{21}(\nu_s)P_s(z)\Gamma_s N_2(z)}{A_c h\nu_s} - \frac{N_2(z)}{t_{21}} + \frac{\sigma_{45}(\nu_p)P_p(z)\Gamma_p N_4(z)}{A_c h\nu_p} - \frac{\sigma_{54}(\nu_p)P_p(z)\Gamma_p N_5(z)}{A_c h\nu_p} - \frac{N_5(z)}{t_{54}} = 0 \quad (1)$$

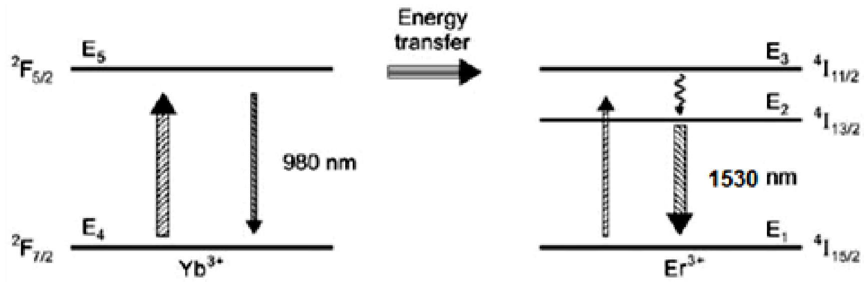

Fig.1. Energy level for the Er/Yb co-doped phosphate fiber [13].

Where Γ_p and Γ_s are the overlapping factors of the pump and the signal light, respectively, A_c is the area of the cross-section of the amplifier, $\sigma_{12}(\nu_s)$ and $\sigma_{21}(\nu_s)$ are the signal absorption and emission cross-section respectively, $\sigma_{13}(\nu_p)$ is the pump absorption cross-section, $\sigma_{45}(\nu_p)$ and $\sigma_{54}(\nu_p)$ are the pump absorption and emission cross-section, respectively, h is Planck's constant.

Letting P_p and P_s be the pump and signal powers in the steady state, respectively, along the EYDFA are described by the power propagation equations which are given by the following equations [13]

$$\frac{dP_p(z)}{dz} = -\Gamma_p[\,\sigma_{13}(\nu_p)N_1(z) + \sigma_{45}(\nu_p)N_4(z) - \sigma_{54}(\nu_p)N_5(z)\,]P_p(z) \quad (2)$$

$$\frac{dP_s(z)}{dz} = \Gamma_s[\,\sigma_{21}(\nu_s)N_2(z) - \sigma_{12}(\nu_s)N_1(z)\,]P_s(z) \quad (3)$$

$$N_1(z) + N_2(z) = N_{Er} \text{ and } N_4(z) + N_5(z) = N_{Yb}, \quad (4)$$

The stimulated emission and absorption transition rates of signal and pump wavelength, are given by

$$W_{12} = \frac{\sigma_{12}\,\Gamma_s\,P_s}{A_c\,h\,\nu_s} \qquad W_{21} = \frac{\sigma_{21}\,\Gamma_s\,P_s}{A_c\,h\,\nu_s}$$

$$W_{13} = \frac{\sigma_{13}\,\Gamma_p\,P_p}{A_c\,h\,\nu_p} \qquad W_{45} = \frac{\sigma_{45}\,\Gamma_p\,P_p}{A_c\,h\,\nu_p}$$

$$W_{54} = \frac{\sigma_{54}\,\Gamma_p\,P_p}{A_c\,h\,\nu_p} \quad (5)$$

where z is the length of the co-doped amplifier, N_{Er} is the erbium concentration and N_{Yb} is the ytterbium concentration.

From Equations (2), (3), (4), (5) and (1) we obtain

$$\frac{1}{A_c h\nu_p}\frac{dP_p(z)}{dz} + \frac{1}{A_c h\nu_s}\frac{dP_s(z)}{dz} + \frac{N_2(z)}{t_{21}} + \frac{N_5(z)}{t_{54}} = 0 \quad (6)$$

By defining $\eta_0 = N_2/(N_2 + N_5)$ as the initial energy transfer efficiency [13], that is, $N_5 = ((1-\eta_0)/\eta_0)N_2$, and letting $B = (\tau_{21}\,\tau_{54})/(\tau_{54} + \tau_{21}(1-\eta_0)/\eta_0)$, Eq.(6) can be rewritten as

$$N_2(z) = -B\frac{1}{A_c h\nu_p}\frac{dP_p(z)}{dz} - B\frac{1}{A_c h\nu_s}\frac{dP_s(z)}{dz} \quad (7)$$

Setting $S = \int_0^z N_2(z)dz$, and then integrating, we can get [13]

$$[G(z)]^{\alpha}\exp[-\alpha\Gamma_s\sigma N_{Er}z] = 1 - \frac{\nu_p P_s(0)[G(z)-1]}{\nu_s P_p(0)} - \frac{\ln G(z) + \Gamma_s\sigma_{12}N_{Er}z}{B\Gamma_s(\sigma_{12}+\sigma_{21})}\frac{A_c h\nu_p}{P_p(0)} \quad (8)$$

Where

$$\alpha = \frac{\Gamma_p\sigma_{13} + \Gamma_p(\sigma_{45}+\sigma_{54})(1-\eta_0)/\eta_0}{\Gamma_s(\sigma_{12}+\sigma_{21})} \quad (9)$$

With $G(z) = P_s(z)/P_s(0)$

$$\sigma = \frac{\sigma_{12}+\sigma_{21}}{\sigma_{13}+(\sigma_{45}+\sigma_{54})(1-\eta_0)/\eta_0}\left(\sigma_{13} + \sigma_{45}\frac{N_{Yb}}{N_{Er}}\right) - \sigma_{12} \quad (10)$$

Where G(z) is the gain of the amplifier.

$$NF_{EDFA} = \frac{1}{G_{EYDFA}} \quad (11)$$

We consider the second amplifier, which is Raman amplifier, the rate equation for Raman amplifier can be written as [14, 15]:

$$\frac{dP_{s2}}{dz} = -\alpha_{s2}P_{s2} + \frac{g_r P_{p2} P_{s2}}{\gamma_p} \quad (12)$$

$$-\frac{dP_{p2}}{dz} = -\alpha_{p2}P_{p2} + \frac{\omega_{p2}}{\omega_{s2}}\frac{g_r P_{p2} P_{s2}}{\gamma_p} \quad (13)$$

where P_{s2} is signal power for Raman amplifier, g_r is Raman gain coefficient, P_{p2} is the pump power for Raman amplifier, γ_p is the cross sectional area of pump beam inside the fiber, α_{s2} and α_{p2} is fiber losses at signal and pump at frequencies (ω_{s2} and ω_{p2}), "-" sign for backward pumping. Because the signal power is small in comparing with pump power of Raman, we can put $g_r = 0$ in equation 13, and by integrating this equation from 0 to z, we can write

$$P_{p2}(z) = P_{p2}(0)e^{\alpha_{p2}z} \quad (14)$$

Now by substituting eqn. 14 in eqn. 12 and let $P_{s2}(0) = P_{s1}(L)$, the output signal power from, solving Eqs. (12)-(14), using Matlab program and Rung - Kutta procedure, we obtain the output signal of RA, which is $P_{s2}(L_R)$

The net gain of HA can be written as

$$G(dB) = 10log_{10}\left(\frac{P_{s2}(L_R)}{P_{s1}(0)}\right) \quad (15)$$

with

The Raman gain coefficient is calculated from the relation [15]:

$$g_r = \gamma_s(\nu)\frac{\lambda_s^3}{c^2 h(n(\nu))^2} \quad (16)$$

γ_s is the Raman cross section of the signal, λ_s is the Stokes wavelength, h Planck's constant and n(ν) is the frequency dependent refractive index.

The net noise figure will calculated as considering EYDFA and Raman amplifier as cascaded amplifiers, for EYDFA noise figure [15]

For Raman amplifier [15]

$$NF_{Raman} = \frac{2P_{ASE}^{-}}{h\nu_{sr}\Delta\nu_r G_{Raman}} + \frac{1}{G_{Raman}} \quad (17)$$

where $\Delta\nu_r$ is the reference optical bandwidth corresponding to 0.1 nm [15], the net noise figure for the purposed system is

$$NF_{net} = \frac{NF_{Raman}}{G_{EYDFA}} \quad (18)$$

The absorption cross section of both erbium and ytterbium was obtained from Refs. [16], and the values of Raman cross section are given in Refs. [17, 18], the other input values of our model are listed in Tables 1, 2 and 3.

Table 1. The parameters of EYDFA

Parameter	**Symbol**	**Value**	**Unit**
Pump wavelength	λ_p	980	nm
Signal wavelength	λ_s	1530	nm
Er concentration	N_{Er}	$5.14x10^{25}$	m^{-3}
Yb concentration	N_{Yb}	$6.2x10^{26}$	m^{-3}
Er^{3+} absorption cross-section	σ_{13}	$2.58x10^{-25}$	m^2
Yb^{3+} absorption cross-section	σ_{45}	$1.0x10^{-24}$	m^2
Yb^{3+} emission cross-section	σ_{54}	$1.0x10^{-24}$	m^2
Er^{3+} absorption cross-section	σ_{12}	$6.5x10^{-25}$	m^2
Er^{3+} emission cross-section	σ_{21}	$7.0x10^{-25}$	m^2
Er^{3+} emission lifetime	τ_{21}	10	ms
Yb^{3+} emission lifetime	τ_{54}	1.5	ms
Initial energy transfer efficiency	η_0	0.115	-
Core refractive index	n_1	1.52812	-
Cladding refractive index	n_2	1.51	-
Amplifier cross-section	A_{eff}	50	μm^2
Pump overlap factor	Γ_p	0.921	-
Signal overlap factor	Γ_s	0.795	-

Table 2. Values of EYDFA/Raman HOA parameters

Parameter	**values**
Raman pump power	100 , 200 mW
EYDFA pump power	100 – 500 mW
Raman amplifier length	25 km
EYDFA length	1 m
Number of input signal channels	44
Number of output signal channels	44

Table 3. RA parameters.

Symbol	Definition	Value
g_r	Raman gain coefficient	10×10^{-14}
$\Delta\nu_r$	Reference optical bandwidth	0.1 nm
λ_p	Pump wavelength	1450 nm
α_{s2}	Fiber loss at signal frequency	2.3×10^{-5} dB/m
α_{p2}	Fiber loss at pump frequency	2.33×10^{-5} dB/m
γ_s	Cross sectional area of pump beam	10.2×10^{12} m^2
γ_p	Cross sectional area of signal beam	11.5×10^{12} m^2

3. Results and discussion

The theoretical model is calculated using equations (10)- (18), with the input parameters given in Tables 1, 2 and 3 are solved using simulation and Matlab program, run every time for every value of the signal wavelength, using the cross section data in Refs.[16- 18].

Fig.2 shows the gain of Er/Yb co-doped fiber /Raman hybrid amplifier (HA) as a function of signal wavelength at different values of Er^{3+} concentration, the gain is calculated at 28.5 dB pump power(500 mW for Er/Yb and 200 mW for RA) at -40 dBm input signal power, 6.2×10^{26} m^{-3} Yb concentration in Er/Yb co-doped fiber amplifier, 1 m Er/Yb fiber amplifier length and 25 km RA length. From the figure, the gain increase with Er concentration increases from 1×10^{25} to 5×10^{25} m^{-3} then decrease for further increase in the Er concentration, furthermore, the gain has two maximum values (49.4 dB at 1530 nm and 43.5 dB at 1600 nm) at Er concentration of 5.12×10^{25} m^{-3}. Fig. 3 shows the noise figure of Er/Yb co-doped fiber /Raman hybrid amplifier (HA) as a function of signal wavelength at different values of Er^{3+} concentration, the gain is calculate at the same conditions of fig. 3. From the figure, the noise figure has a large values for low values of Er concentration at signal wavelength > 1530 nm and minimum values for higher Er concentration at signal wavelength < 1530 nm.

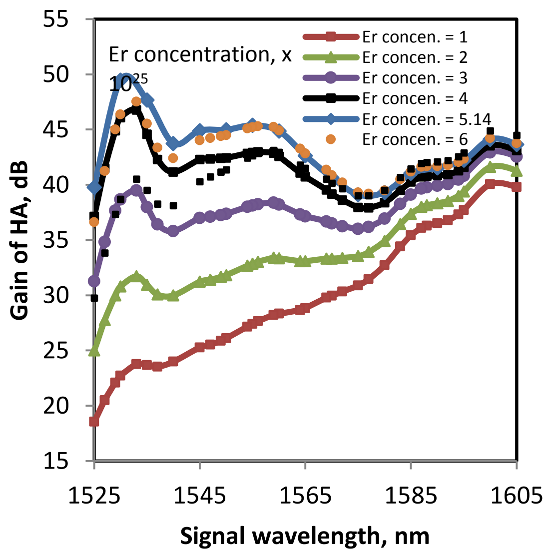

Fig.2. Gain of HA versus signal wavelength at different values of Er^{3+} concentration in m^{-3}.

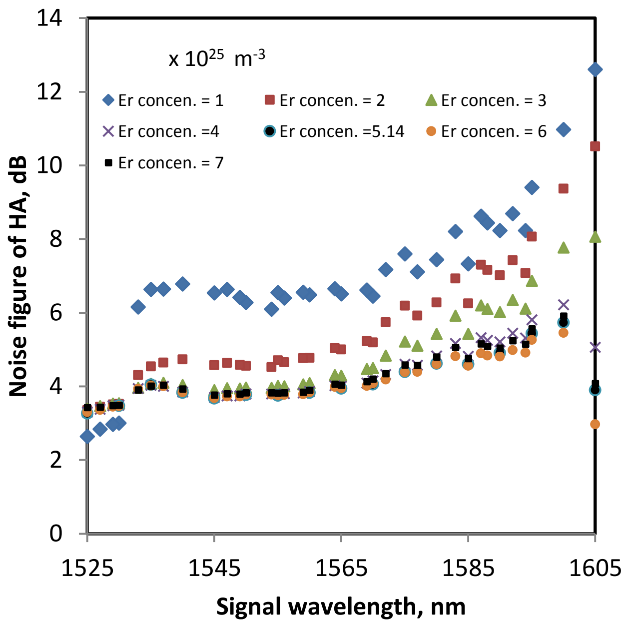

Fig.3. Noise figure of HA versus signal wavelength at different values of Er^{3+} concentration in m^{-3}.

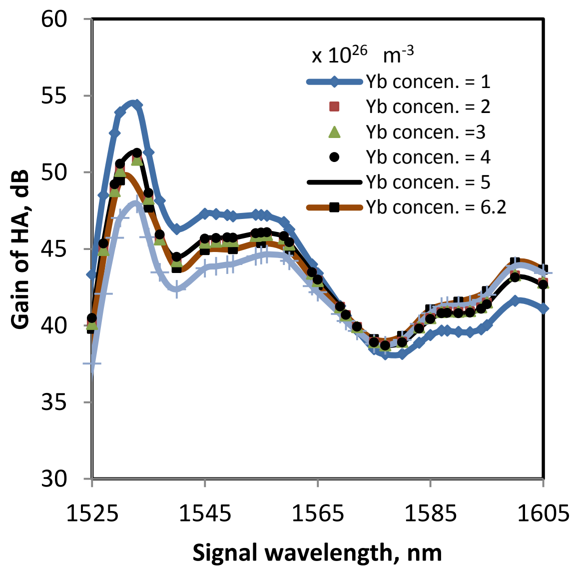

Fig. 4. Gain of HA versus signal wavelength at different values of Yb^{3+} concentration in m^{-3}.

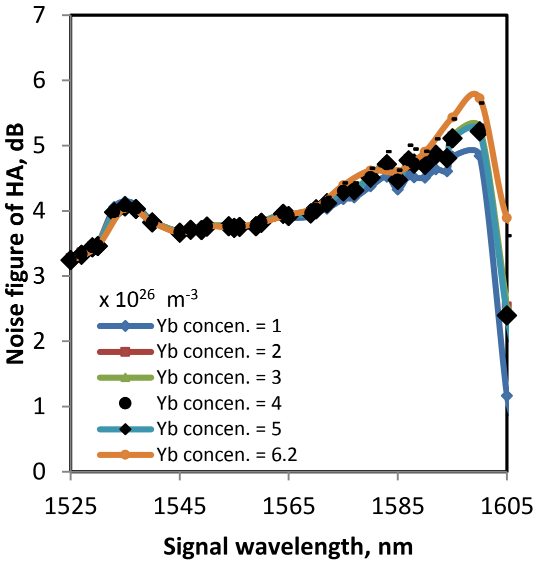

Fig. 5. Noise figure of HA versus signal wavelength at different values of Yb^{3+} concentration in m^{-3}.

Fig. 4 displays the gain of HA as a function of signal wavelength at different values of Yb^{3+} concentration in m^{-3}, the gain is calculated at 1m Er/Yb co-doped amplifier, 25 km RA length, 28.5 dBm dual pump power, -40 dBm input signal power and 5.12 $\times 10^{25}$ m^{-3} Er concentration in Er/Yb co-doped fiber amplifier. It's clear that the gain has a two maximum values of (53.92 dB at 1530 nm and 43.8 dB at 1600 nm) at Yb concentration of 6. 2 $\times 10^{26}$ m^{-3}, furthermore, the gain decrease with Yb concentration increase. The noise figure of HA as a function of signal wavelength at different values of Yb^{3+} concentration in m^{-3}, plotted in Fig.5 at the same conditions of Fig.4, the noise figure has a minimum values of (3.48 dB at 1530 nm and 5.65 dB at 1600 nm) at Yb concentration of 6. 2 $\times 10^{26}$ m^{-3} and decrease slightly as the Yb concentration decrease as in Fig. 5.

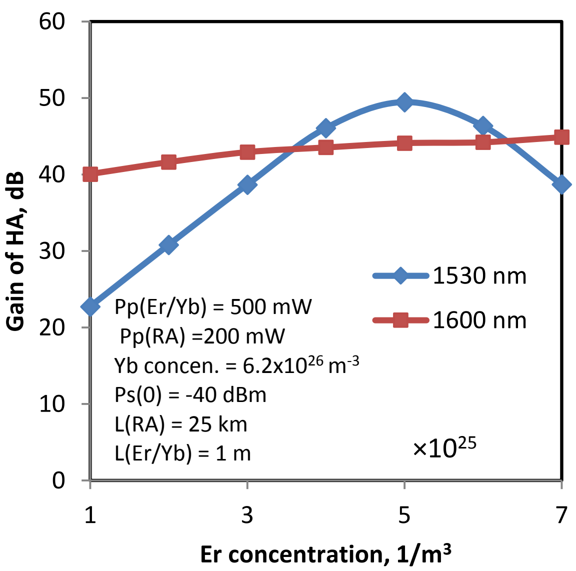

Fig. 6. Gain of HA versus Er^{3+} concentration at two different values 1530 and 1600 nm of signal wavelength.

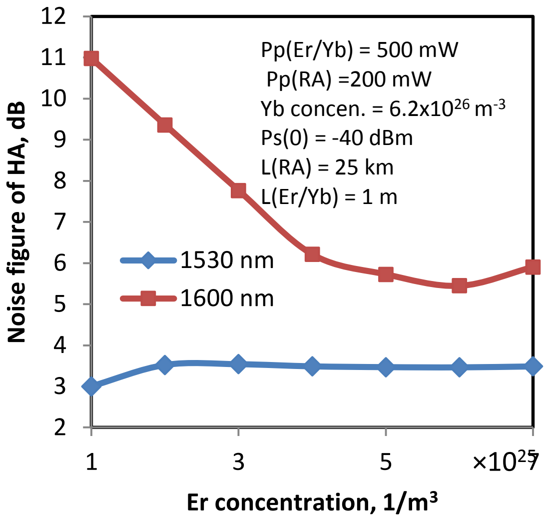

Fig.7. Noise figure of HA versus Er^{3+} concentration at two different values 1530 and 1600 nm of signal wavelength.

The effect of Er^{3+} concentration on the gain and noise figure of HA can be explained in details as in figures 6 and 7 respectively, where the gain and noise figure are plotted against Er^{3+} concentration at fixed value of Yb^{3+} concentration 6.2 $\times 10^{26}$ m^{-3}, Er/Yb co-doped fiber length of 1m, RA length of 25 km, signal power of -40 dBm and 28.5 dBm dual pump power, the gain and noise figure are plotted for two signal wavelengths (1530 and 1600 nm), the wavelength of 1600 nm was chosen as the end spectrum limit. At 1530 nm, the gain has a maximum value(49.47 dB) at Er^{3+} concentration of 5.14 $\times 10^{25}$ m^{-3} and the noise figure has a maximum value (3.52 dB) at at Er^{3+} concentration of 2 $\times 10^{25}$ m^{-3}, the gain decreases for concentration > 5.14 $\times 10^{25}$ m^{-3} and the noise figure is slightly decrease for concentration > 5.14 $\times 10^{25}$ m^{-3}. At 1600 nm, the gain start from large value of 40 dB at Er^{3+} concentration of 1 $\times 10^{25}$ m^{-3} and slightly increases for concentration > 1 $\times 10^{25}$ m^{-3} and the noise figure decrease with increasing Er^{3+} concentration.

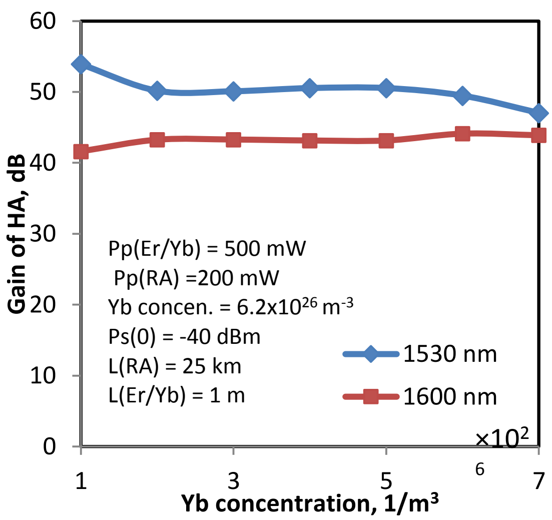

Fig.8. Gain of HA versus Yb^{3+} concentration at two different values 1530 and 1600 nm of signal wavelength.

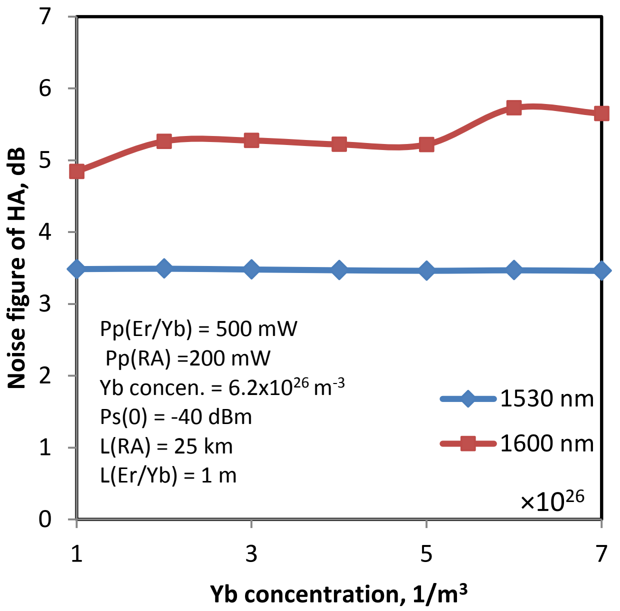

Fig. 9. Noise figure of HA versus Yb^{3+} concentration at two different values 1530 and 1600 nm of signal wavelength.

Furthermore, the effect of Yb^{3+} concentration on the gain and noise figure of HA is shown in figures 8 and 9 respectively, where the gain and noise figure are plotted against Yb^{3+} concentration at fixed value of Er^{3+} concentration 5.14 $\times 10^{25}$ m^{-3}, Er/Yb co-doped fiber length of 1m, RA length of 25 km, signal power of -40 dBm and 28.5 dBm dual pump power, the gain and noise figure are plotted for two signal wavelengths (1530 and 1600 nm). At Yb3+ concentration of 1 $\times 10^{26}$ m^{-3}, the gain has maximum value of (53.9 dB at 1530 nm and 43.2 dB at 1600 nm) and nearly saturated for concentration > 2 $\times 10^{26}$ m^{-3} for both selected signal wavelengths. The noise figure in Fig. 9 has a constant value ~ 3.48 dB at all values of Yb^{3+} concentration at 1530 nm and minimum value of 4.84 dB at Yb3+ concentration of 1 $\times 10^{26}$ m^{-3} and signal wavelength of 1600 nm.

4. Conclusion

In this work we study the effect of concentration of Er^{3+} and Yb^{3+} on the gain and noise figure of hybrid amplifier, which is a combination of two amplifier, Er/ Yb co-doped amplifier of length 1m and Raman amplifier of length 25 km, with dual pumps are used, one forward at 980 nm with power of 500 mW for Er/Yb co-doped and the other pump is backward at 1450 nm with power of 200 mW for Raman amplifier so the total pump power is 700 mW ≈ 28.5 dBm at input signal of -40 dBm at signal wavelength of (1525 – 1610 nm). The hybrid amplifier is purposed for improving the gain and noise figure of the optical amplifier. The host glass used is phosphate, phosphate glasses have their unique characteristics that include high transparency, low melting point, high thermal stability, high gain density that is due to high solubility for lanthanide (Ln) ions, low refractive index and low dispersion. The maximum gain 53.92 dB and minimum noise figure 3.48 dB are obtained for the hybrid amplifier at 1530 nm with 5.14×10^{25} m^{-3} Er concentration and 1×10^{26} m^{-3} Yb concentration , on the other hand the gain shows large values at 1600 nm with the same input parameters listed above due to hybrid Raman amplifier with EYDFA so, a flat gain is observed in the all range of signal wavelength with higher band width.

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