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STUDY OF EFFECT OF INHOMOGENEOUS DISTRIBUTION OF COOPERATIVE UP-CONVERSION COEFFICIENT ON THE OPTICAL AMPLIFICATION PROCESS IN SI-NC AND ER DOPED OPTICAL FIBER

A. Salmanogli and A. Rostami

Photonics and Nanocrystal Research Lab. (PNRL)
Faculty of Electrical and Computer Engineering
University of Tabriz
Iran

Abstract—Effects of different optical losses (auger recombination, cooperative up-conversion, excited state absorption (ESA) and Si-Nc induced loss) on amplification parameters including net gain and population inversion in Si-Nc Er doped fibber are studied. Optical loss due to up-conversion effect has critical role in the mentioned optical amplifiers. Simple modeling of this effect can be done by $2C_{up}N_2^2$, where C_{up} and N_2 are up-conversion coefficient and population of level 2 respectively. In traditional considered cases C_{up} are assumed to be constant, but in practical situation this is hard to be realized. In practice distribution of Er ions is inhomogeneous and especially the Gaussian. So, from our point of view the suitable model should consider position dependence up-conversion coefficient. In this paper we considered this subject and by simulation modeling tries to show effect of inhomogeneous distribution of up-conversion coefficient on optical net gain and population inversion.

It is shown that life times of first and second excited states are decreased and so the population inversion is decreased too. Thus optical net gain near to center of the Gaussian distribution is deceased strongly. The observed gain lowering is suitable description of the reported experimental results. Also, it is observed that in high level Si-Nc density the obtained optical gain is decreased against traditional description which C_{up} is assumed to be constant. The core diameter is considered $R = 10\,\mu\text{m}$.

1. INTRODUCTION

High-speed data communication and processing are basic industrial and scientific demand recently. Optical method is one of best alternatives for doing these tasks. Main physical medium for optical communication and processing is optical fiber. Transmission bit rate in optical communication is higher than other data transmission methods. But, this is still far from the fundamental limit to the information transfer rate, and future systems are expected to reach data transfer rates of several turbits per second in a single fiber, for transmission over large distance the optical signal needs to be amplified at regular intervals in order to maintain sufficient light intensity. There are different alternatives for optical amplification such as semiconductor optical amplifiers (SOA, [1, 2]), Erbium doped fiber amplifier (EDFA) and Si-Nc-Er doped amplifier [3–8]. These amplifiers can be used in optical integrated circuit also to compensate signal losses. Such amplifiers use stimulated emission from the first excited state to the ground state of $Er^{(+3)}$ at 1550 nm the intra-4f transition is parity forbidden, and as a result the emission cross section for EDFA amplifier is quite small ($10^{-21}\,\mathrm{cm}^2$). Consequently, in this amplifier for high gain achievement, high Er concentration is required. At this high Er concentration the closely spaced Er ions can interact. This cause several effect, such as energy migration, in which an excited Er ions excite a neighboring unexcited Er ions, which may in turn be coupled to a nonradiative quenching site, and cooperative up-conversion, in which an excited Er ions promotes a neighboring excited Er ions a higher levels. Both processes are detrimental to the optical gain, as they reduce the population inversion in the first excited state. These interactions between ions affect the optical net gain in Si-Nc-Er doped fiber amplifier. Moreover, in this amplifier Si-Nc induced loss affects the net gain. So that high level Er ions are required to achieve significant gain in waveguide structure in small length (cm) scales [9–12]. The effect of cooperative up-conversion not only depends on the average Er concentration, but also on the microscopic distribution of the Er ions in the host material [13, 14].

In [15, 16] the authors concentrated on Si-Nc Er doped fiber amplifier generally and in these references main focusing done on quantum dot and optical properties of Si-Nc was investigated. Using this idea some features of optical amplifier was extracted and distinguished properties were illustrated. Also, a traditional EDFA and Si-Nc Er doped fiber amplifier was compared. In these references effect of maximum number of excitons in Si-Nc on amplification process didn't discussed.

In [17] modeling of experimentally realized Si-Nc Er doped fiber amplifier was done. In this paper a phenomenological model was presented based on an energy level scheme taking into account the strong coupling between each Si nanocrystal and the neighboring Er ions and considering the interactions between Er ions pairs too, such as the concentration quenching effect and the cooperative up-conversion mechanism. This is an interesting paper, but some critical points such as inhomogeneous distribution [18] of Er-ions didn't addressed. In practice inhomogeneous distribution usually occurred and complete description of experimental results should consider this subject. But, the cooperative up-conversion coefficient was considered constant for whole simulations. Also, it should mention that in all published papers the up-conversion coefficient was assumed to be constant.

Optical losses in presence of Si-Nc Er doped fiber amplifier were discussed in [19, 20]. In these papers scattering loss and optical loss due to inhomogeneity in manufacturing step of waveguide were discussed. Results of this paper can be used for modeling of optical amplifier precisely.

Energy transfer between Si-Nc and Er ions and time constant of energy coupling was discussed in [21, 22]. This paper presents experimental result of silica thin films containing Si nanocrystals and Er ions prepared by ion implementation. Results of this paper can be used for transient analysis of optical amplifier in presence of nanocrystals.

The effect of cooperative up-conversion loss not only depends on the average concentration of Er ions but also depends on the distribution profile of the Er ions in the host material. The Up-Conversion coefficient can vary by orders of magnitudes in the same host material. In this article, we assumed Er distribution in the form of Gaussian profile which this form mainly used in practice. Therefore up-conversion coefficient is a function of core radius ($C_{up}(z)$). Thus it is shown that the radius dependency of the up-conversion coefficient affects the population of first excited state and optical net gain strongly.

The organization of this paper is as follows.

Mathematical background is presented in Section 2. Also, modeling and principle of operation is discussed. Simulation results and discussion is illustrated in Section 3. Finally the paper ends with a short conclusion.

2. MATHEMATICAL BACKGROUND AND PRINCIPLES OF OPERATION OF SI-NC OPTICAL AMPLIFIER

Si-Nc Er doped fiber amplifier is a suitable alternative for decreasing of the fiber [23, 24] length for given gain. In this amplifier Er ions excited indirectly through Si-Nc and because of high absorption cross section of Si-Nc the efficiency of pumping is increased too. Also, in this case large optical bandwidth can be supported and there isn't any requirement to precise laser diode [25, 26] for pumping. Figure 1 typically shows the inhomogeneous distributions of Er ions. Based on this figure it is obvious that the cooperative up-conversion coefficient can't be constant and same at whole place because of inhomogeneous distribution of Er ions. Therefore, we describe $C_{up}(z)$ in this paper for clearly investigation of the effect of interaction between ions in the first excited state.

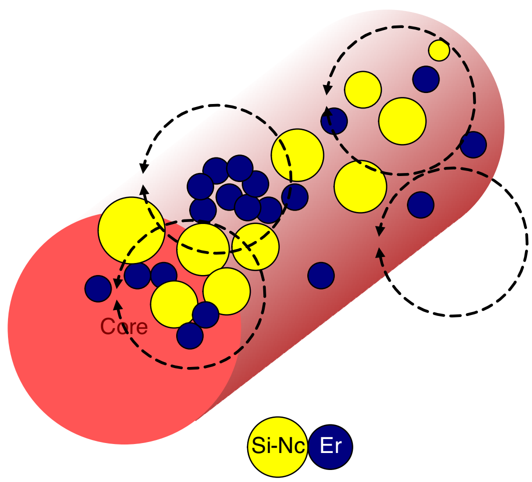

Figure 1. Schematic of inhomogeneous Er ions doped fiber amplifier.

In this analysis silicon nanocrystal behavior can be described by a three level system. Since the reported experimental results show that the trapping is very fast process compared to the typical decay time in optical amplifiers, with accepting a small error two-level case is good approximation for silicon nanocrystals.

The following defined parameters are used in simulation of the optical amplifier.

N_0 Total density of silicon nanocrystal

$N_{a,b}$ Population of level a and b in silicon nanocrystal

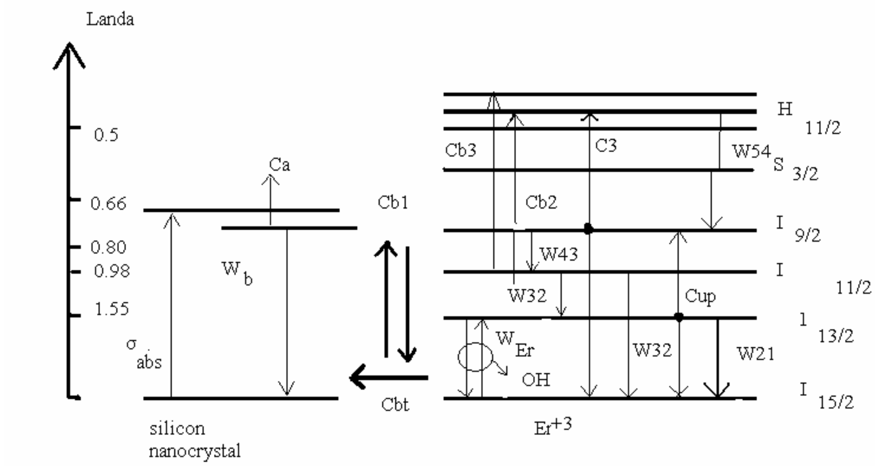

Figure 2. Energy level scheme for the system of interaction Silicon Nanocrystal and Er ions.

N_i Population in different levels (i) of $Er^{(+3)}$ ions
σ_{abs} Si-Nc absorption cross section
ϕ Photon Flux
σ_{dir} Direction absorption cross section
W_{er} The concentration quenching effect (due to the energy migration all over the sample introduced by the energy transfer between two nearby $Er^{(+3)}$ ions occurred between ground and first excited states)
W_b The exiton total recombination rate
W_{ij} The total transition rate from level i to level $j (i > j)$
C_{up} Co-operative up-conversion coefficient
C_{bt} Backward transfer energy from Er to Si-Nc
$C_{bi}(i > 2)$ Excited state excitation (ESA) from level $i (i > 2)$
$C_{bi}(i = 1)$ The coupling between the silicon nanocrystal and the ground state of $Er^{(+3)}$

In the following the rate equations for the proposed system are given based on the continuity equation [17].

$$\frac{dN_b}{dt} = \sigma_{abs}\phi(N_0 - N_b) - (W_b N_b) - \sum_{i=1}^{3} C_{bi} N_b N_i(z) \tag{1}$$

$$\frac{dN_a}{dt} = \sigma_{abs}\phi(-N_0 + N_b) + (W_b N_b) + \sum_{i=1}^{3} C_{bi} N_b N_i(z) \tag{2}$$

$$\begin{aligned}
\frac{dN_5(z)}{dt} &= (C_{dir}\sigma_{dir}\phi N_3(z)) + \left(C_3 N_3(z)^2\right) - (W_{54}N_5(z)) \\
&\quad + \sum_{i=2}^{3} C_{bi}N_bN_i(z) \qquad (3) \\
\frac{dN_4(z)}{dt} &= (W_{54}N_5(z)) + \left(C_{up}(z)N_2(z)^2\right) - (W_{43}N_4(z)) \\
&\quad +(C_{b1}N_1(z)N_b) \qquad (4) \\
\frac{dN_3(z)}{dt} &= (W_{43}N_4(z)) - (W_{32}+W_{31})N_3(z) - \left(2C_3N_3(z)^2\right) \\
&\quad -(C_{b3}N_bN_3(z)) - (C_aN_bN_3(z)) \qquad (5) \\
\frac{dN_2(z)}{dt} &= (W_{32}N_3(z)) - (W_{21}+W_{er})N_2(z) - \left(2C_{up}(z)N_2(z)^2\right) \\
&\quad -(C_{b2}N_bN_2(z)) - (C_aN_bN_2(z)) \qquad (6) \\
\frac{dN_1(z)}{dt} &= (W_{21}+W_{er})N_2(z) + \left(C_{up}(z)N_2(z)^2\right) + (N_2(z) \\
&\quad +N_3(z))C_aN_b + (W_{31}N_3(z)) + \left(C_3N_3(z)^2\right) \\
&\quad -(C_{bt}N_bN_1(z)) - (\sigma_{dir}\phi N_1(z)) \qquad (7)
\end{aligned}$$

In the following table all parameters used in this paper for simulation is given.

3. RESULTS AND DISCUSSION

Based on the proposed rate equations in Section 2, in this section for evaluation of the variation of cooperative up-conversion coefficient effect in the different point of core on parameters of optical amplifier are presented and discussed. For this task, we consider the following cases for simulations.

a) Transient response,

b) Steady state response

In first part (a) of simulations we considered time evaluation of normalized photoluminescence (PL) intensity at 1550 nm (Figures 3 and 4) and 980 nm (Figure 5). In theses curves we assumed steady state condition and the pump turn off in $t = 0$. On the other hand this curve show decay time of the system. So, we expect that the PL decreases with increasing time. In these figures effects of different Er ions concentration and variation of cooperative up-conversion coefficient (DC_{up}) on PL is considered. It is shown that with increasing the Er concentration the PL is decreased. For description of this effect it can point out that in high Er concentration rate of interaction between

Table 1. Physical parameter for simulation of optical amplifier [17].

Symbol	**Value**
λ_{exc}	$488\,\mathrm{nm}$
σ_{abs}	$2 \cdot 10^{-16}\,\mathrm{cm}^2$
σ_{dir}	$1 \cdot 10^{-20}\,\mathrm{cm}^2$
W_b	$2 \cdot 10^4\,\mathrm{s}^{-1}$
W_{21}	$4.2 \cdot 10^2\,\mathrm{s}^{-1}$
W_{32}	$4.2 \cdot 10^5\,\mathrm{s}^{-1}$
W_{43}	$1 \cdot 10^7\,\mathrm{s}^{-1}$
W_{54}	$< 1 \cdot 10^7\,\mathrm{s}^{-1}$
C_{b1}	$3 \cdot 10^{-15}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$
C_{up0}	$7 \cdot 10^{-17}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$
C_{b2}	$< 3 \cdot 10^{-19}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$
C_{b3}	$< 3 \cdot 10^{-19}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$
C_{bt}	$< 3 \cdot 10^{-19}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$
C_a	$< 3 \cdot 10^{-19}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$
C_3	$7 \cdot 10^{-17}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$
W_{er}	$8.1 \cdot 10^{-19} N_{Totaler}\,\mathrm{s}^{-1}$

ions is increased and so PL is decreased. Moreover, these figures show that there is considerable reduction in magnitude of PL in the case of variable up-conversion coefficient compared constant and uniform case. It comes back to this fact that in the case of variable up-conversion coefficient near the maximum peak of this coefficient due to strong interaction between ions the life time is strongly decreased. In this section solid line refers to the constant C_{up}.

Figures 6 and 7 shows the normalized photoluminescence intensity calculated at 1550 nm as a function of time after switching on the laser beam at $t = 0$. It is observed that the rise time of photoluminescence signal is decreased with decreasing of Er concentration. We defined the typical experimental rise time τ_{on} as the time it takes the luminescence signal to reach the 63% of the saturation value. Moreover, we show that in the case of variable up-conversion coefficient which is illustrated in Figure 7 the steady state value of PL is decreased. This event comes back to increase of introduced loss due to strong interaction between Er ions. Finally in Figure 6, PL intensity for variable and constant up-conversion coefficients have same results because of the

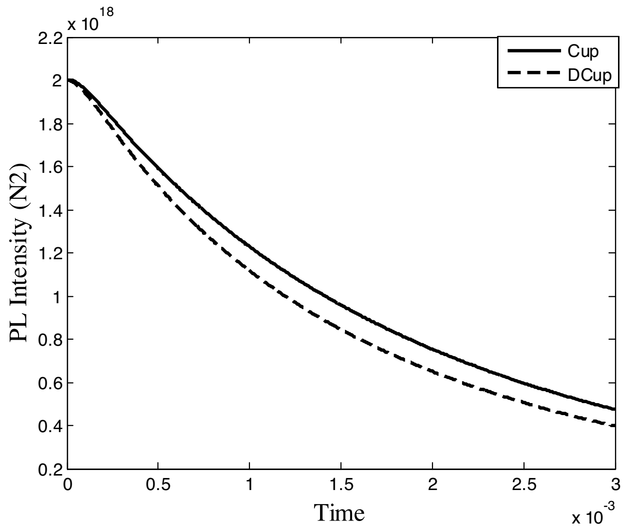

Figure 3. PL intensity life time vs. time (sec). *Mp (Maximum Er Concentration)* $= 1 \cdot 10^{18}$ $(1/\text{cm}^3)$, *Pump* $= 5 \cdot 10^{22}$ Photon.cm^{-2} sec^{-1}. Non-constant cooperative up-conversion coefficient (DC_{up}).

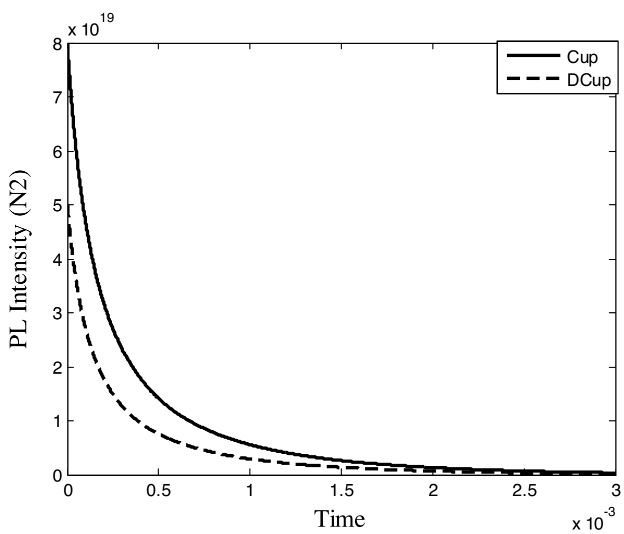

Figure 4. PL intensity life time vs. time (sec). *Mp (Maximum Er Concentration)* $= 1 \cdot 10^{21}$ $(1/\text{cm}^3)$, *Pump* $= 5 \cdot 10^{22}$ Photon.cm^{-2} sec^{-1}.

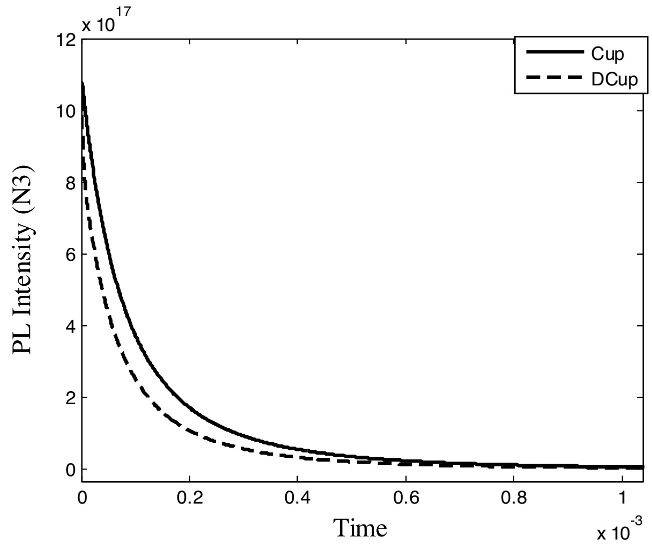

Figure 5. PL intensity life time vs. time (sec). *Mp (Maximum Er Concentration)* $= 1 \cdot 10^{21}$ (1/cm^3), *Pump* $= 5 \cdot 10^{22}$ Photon.cm^{-2} sec^{-1}.

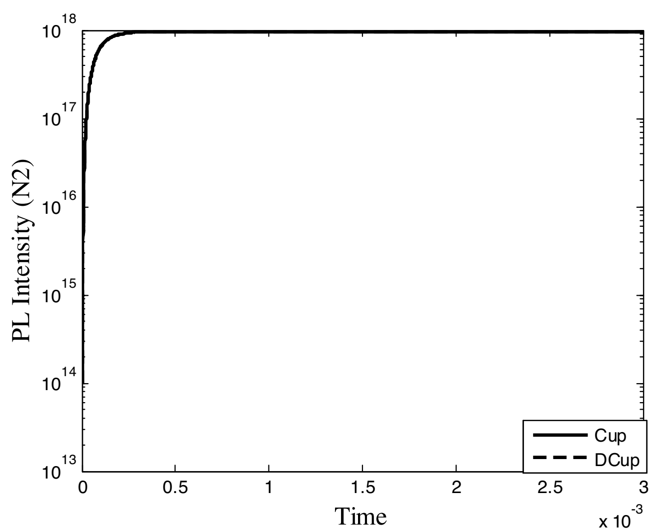

Figure 6. PL intensity rise time vs. time (sec). *Mp (Maximum Er Concentration)* $= 1 \cdot 10^{18}$ (1/cm^3), *Pump* $= 1 \cdot 10^{20}$ Photon.cm^{-2} sec^{-1}.

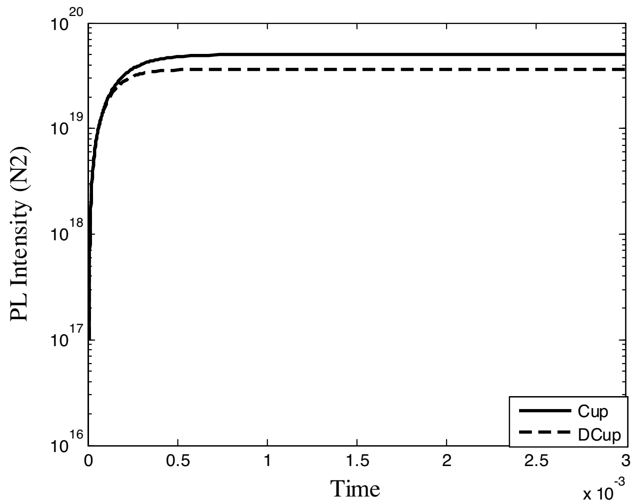

Figure 7. PL intensity rise time vs. time (sec). *Mp (Maximum Er Concentration)* $= 1 \cdot 10^{21}$ (1/cm^3), *Pump* $= 1 \cdot 10^{20}$ Photon.cm^{-2} sec^{-1}.

small interaction due to low Er ions concentration.

In second part (b) we consider steady state condition. In Figures 8 and 9, effects of variation of Si-Nc density and cooperative up-conversion coefficient on the exited Si-Nc and population inversion are investigated and it is considered ($\sigma_{Er} = 3\,\mu\text{m}$) at Er distribution profile. It is shown that with increase of the Si-Nc density, excited state Si-Nc and population inversion are decreased which this event comes back to increase of the coupling between Er ions and Si-Nc. Moreover, we investigated the effect of variation of cooperative up-conversion coefficient on the excited state Si-Nc and population inversion. We observed that in the distances near to center of the Gaussian distribution of Er ions, reduction of excited Si-Nc population inversion are increased due to increase of the interaction between Er ions at the center of Gaussian distribution. In these figures $N\,2si{-}nc(Si{-}Nc\,Concentration)$, $N\,1si{-}nc(Si{-}Nc\,Concentration)$ are maximum and minimum concentrations of the $Si - Nc$, respectly. Other parameter that used in these figures is Mp which illustrated the maximum number of Er concentration.

As another simulation we considered effect of variable up-conversion coefficient on optical gain and net gain. We observed that in the case of variable up-conversion coefficient decrease of optical gain and net gain around peak of Er ions and peak of the coefficient are considerable. Effect of density of Si-Nc on optical gain is considered.

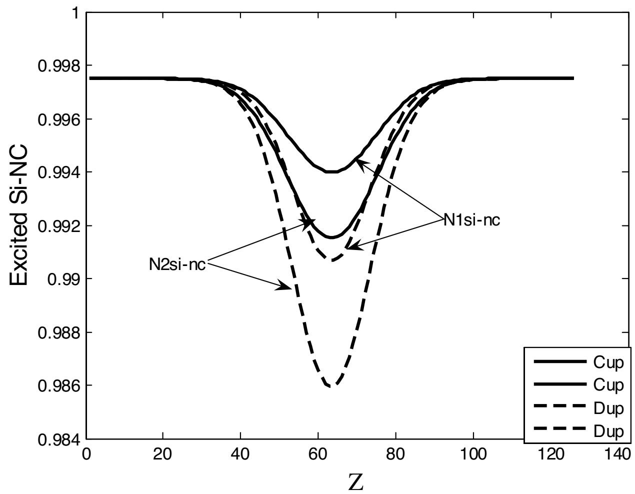

Figure 8. Excited Si-Nc vs. Z. *Mp(Maximum Er Concentration)* $= 1 \cdot 10^{20}\,(1/\text{cm}^3)$, $\sigma_{Er} = 3\,\mu\text{m}$, *Pump* $= 5 \cdot 10^{22}\,\text{Photon.cm}^{-2}\,\text{sec}^{-1}$. $N2si-nc(Si-Nc\ Concentration) = 2 \cdot 10^{19}\,(1/\text{cm}^3)$, $N1si-nc(\,Si-Nc\ Concentration) = 1 \cdot 10^{19}\,(1/\text{cm}^3)$.

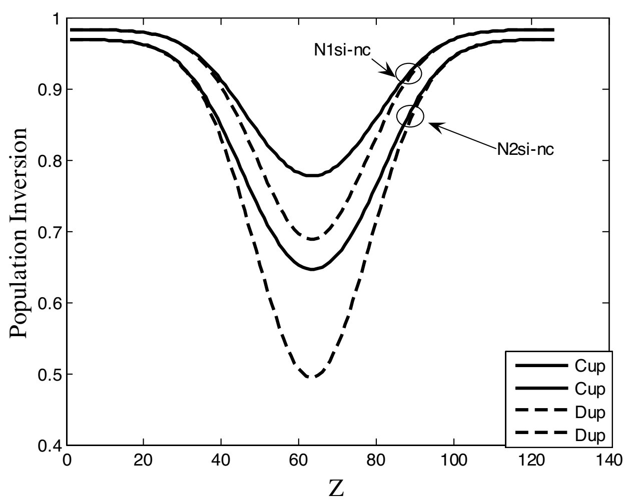

Figure 9. Population inversion vs. Z. *Mp(Maximum Er Concentration)* $= 1 \cdot 10^{20}\,(1/\text{cm}^3)$, $\sigma_{Er} = 3\,\mu\text{m}$, *Pump* $= 5 \cdot 10^{22}\,\text{Photon.cm}^{-2}\,\text{sec}^{-1}$. $N1si-nc(Si-Nc\ Concentration) = 1 \cdot 10^{19}\,(1/\text{cm}^3)$, $N2si-nc(\,Si-Nc\ Concentration) = 2 \times 10^{19}\,(1/\text{cm}^3)$.

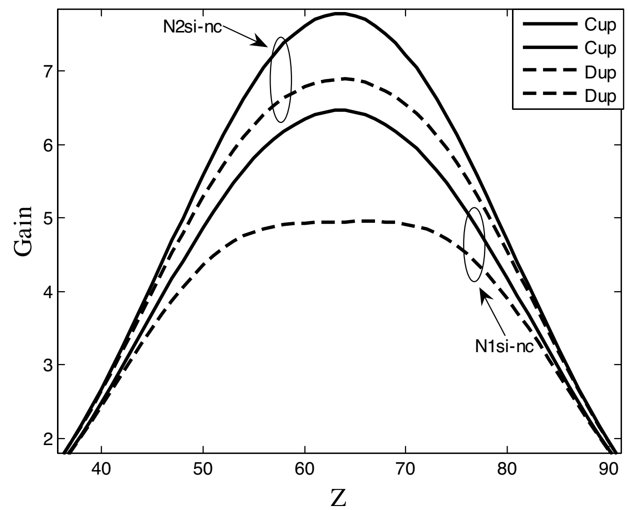

Figure 10. Gain vs. Z. *Pump* $= 1 \cdot 10^{20}$ Photon.cm^{-2} sec^{-1}, *Mp(Maximum Er Concentration)* $= 1 \cdot 10^{20}$ (1/cm^3), $\sigma_{Er} = 3\,\mu$m, $N2si-nc(\,Si-Nc\ Concentration) = 2 \times 10^{19}$ (1/cm^3), $N1si-nc(\,Si-Nc\ Concentration) = 1 \times 10^{19}$ (1/cm^3).

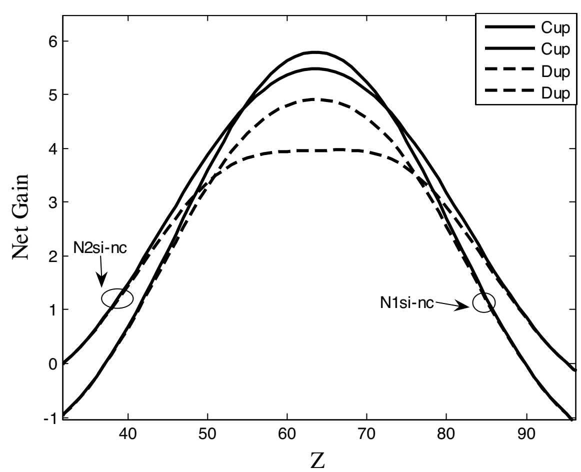

Figure 11. Net gain vs. Z. *Mp(Maximum Er Concentration)* $= 1 \cdot 10^{20}$ (1/cm^3), *Pump* $= 5 \cdot 10^{22}$ Photon.cm^{-2} sec^{-1}, $\sigma_{Er} = 3\,\mu$m. $N1si-nc(Si-Nc\ Concentration) = 1 \times 10^{19}$ (1/cm^3), $N2si-nc(Si-Nc\ Concentration) = 2 \times 10^{19}$ (1/cm^3).

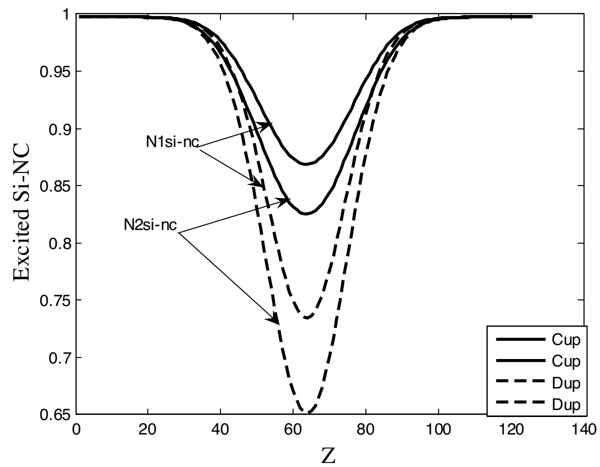

Figure 12. Excited Si-Nc vs. Z. *Mp(Maximum Er Concentration)* = $1 \cdot 10^{21}\,(1/\mathrm{cm}^3)$, $\sigma_{Er} = 2.5\,\mu\mathrm{m}$, $Pump = 5 \cdot 10^{22}\,\mathrm{Photon.cm}^{-2}\,\mathrm{sec}^{-1}$. $N1si-nc(Si-Nc\ Concentration) = 1 \times 10^{19}\,(1/\mathrm{cm}^3)$, $N2si-nc(Si-Nc\ Concentration) = 2 \times 10^{19}\,(1/\mathrm{cm}^3)$.

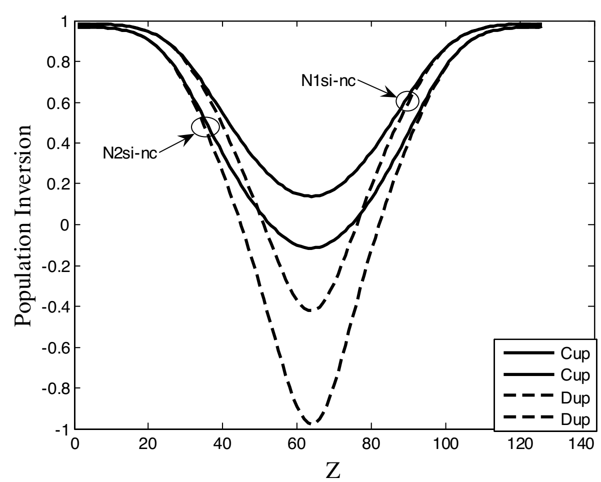

Figure 13. Population inversion vs. Z. *Mp (Maximum Er Concentration)* $= 1 \cdot 10^{21}\,(1/\mathrm{cm}^3)$, $\sigma_{Er} = 2.5\,\mu\mathrm{m}$, $Pump = 5 \times 10^{22}\,\mathrm{Photon.cm}^{-2}\,\mathrm{sec}^{-1}$. $N1si-nc(Si-Nc\ Concentration) = 1 \cdot 10^{19}\,(1/\mathrm{cm}^3)$, $N2si-nc(Si-Nc\ Concentration) = 2 \cdot 10^{19}\,(1/\mathrm{cm}^3)$.

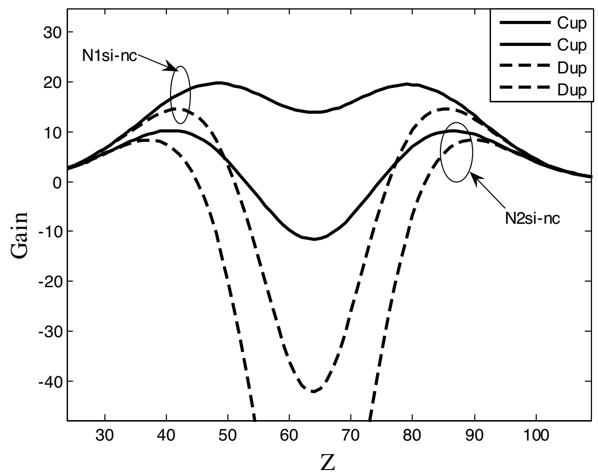

Figure 14. Gain vs. Z. *Mp (Maximum Er Concentration)* $= 1 \cdot 10^{21}\,(1/\mathrm{cm}^3)$, *Pump* $= 5 \cdot 10^{22}\,\mathrm{Photon.cm^{-2}\,sec^{-1}}$, $\sigma_{Er} = 2.5\,\mu\mathrm{m}$. $N1si-nc(Si-Nc\ Concentration) = 1 \cdot 10^{19}\,(1/\mathrm{cm}^3)$, $N2si-nc(Si-Nc\ Concentration) = 2 \cdot 10^{19}\,(1/\mathrm{cm}^3)$.

It is shown that in this case with increase of the density of Si-Nc first the up-conversion coefficient is increased and then optical gain is decreased. The proposed idea easily can be shown in optical net gain.

Finally we considered effect of sharp Gaussian distribution realized by Ion Implantation method on variable up-conversion coefficient and finally on normalized Si-Nc excited state, population inversion and gain factors and it is considered ($\sigma_{Er} = 2.5\,\mu\mathrm{m}$) at Er distribution profile. It is observed that in this case due to sharp variation of the up-conversion coefficient Si-Nc excited state really depleted due to reflected energy. Also, due to this problem the population inversion is destroyed and finally optical gain has minus gain in central part of the core. This effect will damage the light propagation through this amplifier generally.

In this section effect of variable up-conversion coefficient on parameters of the fiber amplifier was considered and it was shown that this is critical generally and should be considered in practice for description of experimental results.

4. CONCLUSION

Si-Nc Er doped fiber amplifier for high quality optical links was studied from different point of views. We have shown that in the case of inhomogeneous distribution of Er ions which is traditional in practice the up-conversion coefficient is variable in core and effect of this phenomenon on characteristics of optical amplifier was modeled and simulated. Our simulations have shown that it is critical and must be considered for precise description of the experimental results. Also, inhomogeneous distribution of Er ions and Si-Nc may be random profile that is difficult to model this system. Moreover, when distribution of Si-Nc and Er ions is inhomogeneous, three factors can affect on the maximum gain and system losses, these factors are minimum distance between Si-Nc and Er ions, maximum size of Si-Nc and anaocrystal materials. These factors can be critical point in simulation and design. The effect, size of Si-Nc and distance between Si-Nc and Er ions is investigated but nanocrystal materials can be affected on constant cooperative up-conversion coefficient and other constants such as Si-Nc absorption cross section, backward transfer energy from Er to Si-Nc, Direction absorption cross section and ect which these parameters can alter population inversion and system gain.

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