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Effects of inhomogeneous distribution of Si–Nc and Er ions on optical amplification in Si–Nc Er doped fiber

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ABSTRACT

In this article, the effects of Si–Nc and Er^{3+} ions distribution parameters including inhomogeneous and homogeneous distribution profile are studied on the optical parameters such as gain, population inversion and Si–Nc induced losses. We have shown that by increasing of the concentration of Si–Nc particles the net gain and induced Si–Nc losses increased in homogeneous and inhomogeneous distributions. In practice, the homogeneous distribution of Er ions and Si–Nc is hard to be realized. Therefore, the inhomogeneous distributions of ions cased to perturb state in mode shape of optical signal then the investigations of those effects are important for high speed optical communications. In this article, a method for evaluation of the effects of inhomogeneous distribution of impurities on performance of optical amplifier is developed and the managing of the gain with use of suitable distribution functions is proposed.

1. Introduction

Optical amplifiers are one of key elements in optical communications and related links. Traditional erbium doped fiber amplifiers (EDFA) and semiconductor optical amplifiers (SOA) [1,2] are popular element and are widely used in WDM and dense WDM (DWDM). These amplifiers have advantage to avoid making multiple opto-electronic conversions since they amplify all signals simultaneously in the optical domain without depending for demultiplex. However, in spite of those noticeable advantages, the modern optical communication can have multiple components such as expensive laser, optical isolators and filters. Moreover, in order to achieve sufficient optical gain, the traditional EDFA usually requires several meters of Er-doped fiber length. So that, for elimination of these disadvantages, Si–Nc is doped to the optical fiber. In such system, the input signals at 1.55 μm are amplified through indirect excitation of Er ions by silicon nanocrystal [3]. Therefore, by indirectly pumping Er ions in presence of nanocrystals, the length of fiber amplifier is drastically reduced for achieving of positive high gain. Also, bandwidth of amplification is broadened due to doping of Si–Nc. This is mainly due to broad absorption band and high absorption cross-section of Si–Nc. For description of operation of Si–Nc Er doped fiber amplifier there are so interesting published papers which we are going to review some of them.

One of important idea, as it is discussed above, is using nanotechnology for improving amplification process. It was shown that the adding silicon nanocrystals to Er doped SiO_2 strongly enhances the effective Er absorption cross-section [4–6]. Also, it was shown that nanocrystals doped into fiber causes the excitations of Er ions compared traditional EDFA through a strong coupling mechanism. This energy transfer process could enable the fabrication of an optical amplifier operating at 1.55 μm that is optically excited at pump intensities as low as a few mW/cm^2. We think that beside of the reported results, adding Si–Ncs into Er-doped optical fiber can decrease fiber length for given gain. Also, Si–Ncs have large absorption cross-section area which is so interesting property for increasing the absorption coefficient of the pump wave, concluding to decrease of pump loss or increase of quantum efficiency. Also, because of large quantum confinement of Si–Nc the appeared band gap is increased compared bulk SiO_2 matrix. This property concludes to absorption of visible light. Due to this effect, the amplifier bandwidth also can be increased [7–10].

In [11–13] 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. The using of those ideas some features of optical amplifier was extracted and distinguished properties were illustrated. Also, a traditional EDFA and Si–Nc Er-doped fiber amplifier were compared. But, the effects of maximum number of excitons in Si–Nc on amplification process did not discuss.

In [14] modeling of experimentally realized Si–Nc and Er doped fiber amplifier was done. In this paper, a phenomenological model based on an energy level scheme was presented. Also, the strong

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coupling between each Si nanocrystal and the neighboring Er ions and considering the interactions between pairs of Er ions, such as the concentration quenching effect and the cooperative up-conversion mechanism were investigated. This is an interesting paper, but some critical points such as inhomogeneous distribution of Er-ions did not address. In practice inhomogeneous distribution usually occurred and complete description of experimental results should be considered.

Optical for Si–Nc Er doped fiber amplifiers were discussed in [15,16,20–22]. In these papers, the scattering losses and optical losses due to inhomogeneity in manufacturing step of waveguide were discussed. Moreover, the effects of optical amplifier parameters are studied on dispersion curve. Results of those papers 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 [17]. This paper presented 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.

Finally, the gain limiting factors in Si–Nc Er doped fiber amplifier was discussed and addressed in [15]. Presented materials in this paper is interested for finding the root of gain limitation in this structure.

In [18] excitation mechanism of Er ions by Si–Nc was discussed and based on the developed method rate of energy exchange between nanocrystal and Er ions is calculated and shown that microsecond time is attainable. One of assumption of this paper is each Si–Nc can support 1–2 Er ions and based on this assumption, they shown that maximum optical gain will be 0.6 dB cm^{-1}. All calculations are based on homogeneous distributions for Er and Si–Nc particles.

Effect of concentration quenching in Er implanted alkali silicate glasses was presented in [19]. They have shown that by increasing concentration of Er ions the population of level two is decreased. In all of those papers, there is no information about inhomogeneous distribution of Si–Nc and Er ions. Inhomogeneous distributions of these particles have significant effect on propagating mode shape and concluding to distortion of energy propagating shape. For this reason, we consider this subject. In this paper, we consider effects of inhomogeneous distributions of Si–Nc and Er ions on optical amplification process in fiber. For this purpose, the Gaussian distributions are assumed. Two critical cases including same and different center and peak of distributions for nanocrystals and Er ions are studied. For simulation of effects of inhomogeneous distributions the numerical solution of the rate equations is used. We observed that the using of suitable distribution profiles can be managed the shape and intensity of gain. Also, the important assumptions for the Gaussian distribution of Si–Nc particles and Er ions are $\sigma_{\text{Si–Nc}} < \sigma_{\text{Er}}$ and same distribution peaks.

The organization of this paper is as follows.

Mathematical background is presented in Section 2. In Section 3 simulated results and discussion is illustrated. Finally the paper ends with a short conclusion.

2. Mathematical background and principles of operation of Si–Nc optical amplifier

Si–Nc and Er doped fiber amplifier is a suitable alternative for decreasing of the fiber length for given gain. In this amplifier, the 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, the large optical bandwidth can be supported and the need for precise laser diode is lighten.

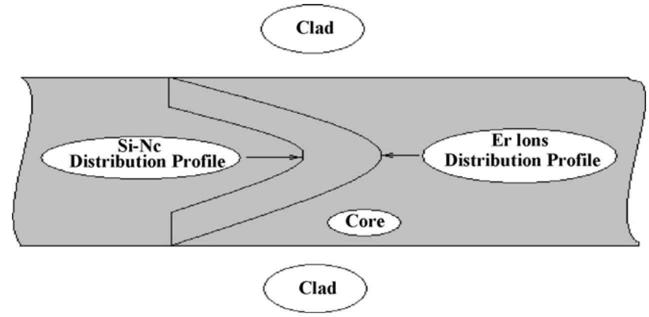

Fig. 1. Schematic of inhomogeneous Si–Nc Er doped fiber amplifier.

Table 1
Physical parameter taken from Ref. [14] that used in rate equations.

Symbol	Value
λ_{exc}	488 nm
σ_{abs}	2×10^{-16} cm^2
σ_{dir}	1×10^{-20} cm^2
W_b	2×10^{4} s^{-1}
W_{21}	4.2×10^{2} s^{-1}
W_{32}	4.2×10^{5} s^{-1}
W_{43}	1×10^{7} s^{-1}
W_{54}	$<1 \times 10^{7}$ s^{-1}
C_{b1}	3×10^{-15} cm^3 s^{-1}
C_{up1}	7×10^{-17} cm^3 s^{-1}
C_{b2}	$<3 \times 10^{-19}$ cm^3 s^{-1}
C_{b3}	$<3 \times 10^{-19}$ cm^3 s^{-1}
C_{bt}	$<3 \times 10^{-19}$ cm^3 s^{-1}
C_a	$<3 \times 10^{-19}$ cm^3 s^{-1}
C_3	7×10^{-17} cm^3 s^{-1}
W_{er}	8.1×10^{-19} N_{Totaler} s^{-1}

In this section, the basic principle of operation and mathematical formulation of inhomogeneous distribution by using of rate equations are discussed and presented. Fig. 1 shows the Gaussian distributions for Si–Nc and Er ions. Based on this figure, it is obvious that in the central part of the fiber the concentrations of particles are high and so optical gain will be high, then the central part of the input pulse more than other parts is amplified and introduces signal distortion in mode shape. In the following, we study the effect of this type of distribution on optical amplification process and try to improve gain and other interesting parameters of optical amplifier. Moreover, two cases including similar distribution of Er ions and Si–Ncs (Gaussian profiles with same position of peak values) and shifted Gaussian profiles with same parameters in first case are explored.

According to presented papers and experimental results two- and five-level models for Si–Nc and Er ions can be used. The following rate equations based on these models can be expressed (Table 1).

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

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

$$\frac{dN_5(z)}{dt} = (C_{dir}\sigma_{dir}\phi N_3(z)) + (C_3 N_3(z)^2) - (W_{54} N_5(z)) + \sum_{i=2}^{3} C_{bi} N_b(z) N_i(z) \quad (3)$$