Paper

Theoretical Studies on Dynamic Characteristics of Yb-Sensitized Er-Doped Garnet Crystal Waveguide-Type Optical Amplifiers

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Amplifiers doped with Ytterbium and Erbium ions are given increasing attention for amplification of signals in the present communication wavelength band of 1.55 μm. Sensitization of Er-doped amplifiers has many advantages such as the possibility of using broader pumping wavelength range. In this paper a thin-film waveguide amplifier based on Er-Yb codoped Garnet crystals is proposed and steady state and transient amplification characteristics, studied numerically using time-dependent rate equations are presented. Understanding the dynamic characteristics of the integrated optic waveguide amplifiers is necessary when the input signal is modulated in various formats. Amplification and pulse distortion effects of short signal pulses are presented, which are shown to be related to the lifetime of the excited states. Comparison is made between the gain characteristics of Er and Er-Yb doped waveguide amplifiers.

Keywords: optical amplifiers, waveguides, dynamic response, rare-earth ions, garnet crystal

1. Introduction

Optical integrated-type amplifiers have attracted attention in the areas of communication and signal processing as amplification and loss compensation devices. They are identified as the key devices to realize integration with other devices (modulators, switches, isolators, etc.) in an optical circuit [1-5]. For these applications in the integrated optical circuits, they have additional advantages such as compactness when compared to fiber and in contrast to semiconductor amplifiers, they are compatible with dielectric waveguides. Waveguide-type amplifiers fabricated using a variety of materials such as silica and $LiNbO_3$ have so far been reported in the literature [3,4,10]. Garnet material is one of the potential candidates for the fabrication of active integrated optical devices. Using these devices small, compact and high efficiency amplifiers can be realized which can be applied to integrated repeaters in FTTH optical communication of broadband access systems and integrated signal processing.

One of the authors has earlier reported a theoretical investigations of waveguide amplifier using Nd-doped Yttrium Gallium Garnet (YGG) thin films on Yttrium Aluminum Garnet (YAG) substrate, and an experimental high gain of 15 dB/cm at 1.064 μm signal wavelength [1,7]. The pump efficiency of Er-doped amplifiers can be improved by codoping with Yb, which acts as sensitizer with larger absorption cross-section than only Er-doped amplifiers [4,8]. They also reported to have advantages including the possibility of using broader pumping wavelength range [8].

Detailed experimental and theoretical results on steady state and transient gain dynamic properties of Yb-sensitized Er-doped garnet crystal waveguide amplifiers have so far not been reported in the literature. In the present research, a thin-film waveguide amplifier based on Yb-sensitized Er-doped Garnet crystals is proposed, and steady state and transient amplification characteristics are studied numerically using time-dependent rate equations and mode propagation equations. The potential of the amplifier for integration with active devices operating at the present communication wavelength of 1.55 μm band is revealed. Steady state response of the Yb-sensitized Er doped Garnet crystal waveguide amplifiers has been analyzed in order to optimize the gain characteristics, which are further used in the dynamic response analysis. The dynamics of the medium is explained by considering input signal pulses with duration comparable with the lifetime of the excited states. Pulses of different shapes have also been considered. Comparison studies have been carried out between the cases of only Er-doped [5] and Er-Yb codoped waveguide amplifiers.

2. Rate equations of radiation in amplifiers

In this section, we present the rate equations with regard to the combined Er-Yb system. We present the theoretical considerations for the case of single mode and two-dimensional waveguide amplifier. The proposed waveguide amplifier is shown in Fig.1. The amplifier consists of Er or Er-Yb doped YGG thin film fabricated on YAG substrate. Three-dimensional waveguiding can be realized by strip-loading the thin-film using ZnO as demonstrated for Nd-doped waveguide amplifier [3]. The simplified energy level diagram and the major transition rates [8,13] are shown in Fig.2. Optical electric fields are given by,

$$\boldsymbol{E}_i(x,y,z,t) = \boldsymbol{E}_i(x,y)a_i(z,t), \quad i = s,p \quad \cdots\cdots (1)$$

where, $\boldsymbol{E}_i(x,t)$ and a_i are transverse fields and amplitudes of the propagating modes of waveguide for signal and pumping optical waves of s and p. The rate of change in the population of the Yb^{3+} energy levels can be written as follows [5,10-12], where superscript 'Yb' is used only for the case of Ytterbium ions to differentiate from Er-ions.

$$\frac{\partial N_1^{Yb}}{\partial t} = -R_{12}^{Yb}N_1^{Yb} + R_{21}^{Yb}N_2^{Yb} + A_{21}N_2^{Yb} + K_{tr}N_2^{Yb}N_1 - K_{ba}N_1^{Yb}N_3 \quad \cdots\cdots (2)$$

$$\frac{\partial N_2^{Yb}}{\partial t} = R_{12}^{Yb}N_1^{Yb} - R_{21}^{Yb}N_2^{Yb} - A_{21}N_2^{Yb} - K_{tr}N_2^{Yb}N_1 + K_{ba}N_1^{Yb}N_3 \quad \cdots\cdots (3)$$

$$N_0^{Yb} = N_1^{Yb} + N_2^{Yb} \quad \cdots\cdots (4)$$

Similarly, the rate of change in the population of the Er^{3+} energy levels are,

$$\frac{\partial N_1}{\partial t} = A_{21}N_2 + W_{12}N_2 - W_{12}N_1 - R_{13}N_1 + R_{31}N_3 + C_{up}N_2^2 - K_{tr}N_2^{Yb}N_1 + K_{ba}N_1^{Yb}N_3 \quad \cdots (5)$$

$$\frac{\partial N_2}{\partial t} = A_{32}N_3 - A_{21}N_2 - W_{21}N_2 + W_{12}N_1 - 2C_{up}N_2^2 \quad \cdots\cdots (6)$$

$$\frac{\partial N_3}{\partial t} = -A_{32}N_3 + R_{13}N_1 - R_{31}N_3 + A_{43}N_4 + K_{tr}N_2^{Yb}N_1 - K_{ba}N_1^{Yb}N_3 \quad \cdots\cdots (7)$$

$$\frac{\partial N_4}{\partial t} = C_{up}N_2^2 - A_{43}N_4 \quad \cdots\cdots (8)$$

$$N_0 = N_1 + N_2 + N_3 + N_4 \quad \cdots\cdots (9)$$

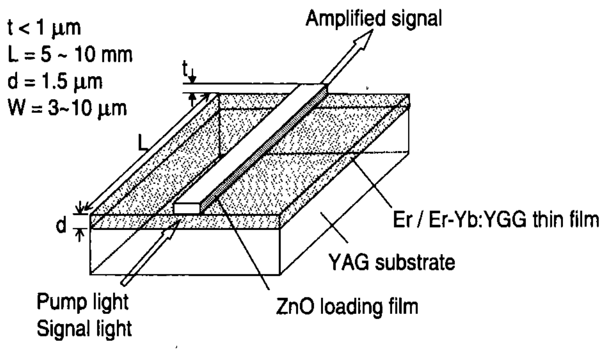

Fig. 1: Structure of Er:YGG/YAG waveguide amplifier.

The population densities $N_1^{Yb}(x,y,z,t)$, $N_2^{Yb}(x,y,z,t)$, $N_1(x,y,z,t)$, $N_2(x,y,z,t)$, $N_3(x,y,z,t)$ and $N_4(x,y,z,t)$ of the corresponding energy levels are as shown in Fig.2. N_0 and N_0^{Yb} are the total population density or the erbium and ytterbium ion concentration respectively. The transition rates are labeled as follows: R_{21}^{Yb} and R_{12}^{Yb} are the pump emission rate and absorption rate of ytterbium respectively. W_{12} and W_{21} are the signal absorption and emission rates. R_{13} and R_{31} are the pump absorption and emission rates. $A_{21}^{Yb}(= 1/\tau_{21}^{Yb})$, $A_{32}(= 1/\tau_{32})$ and $A_{21}(= 1/\tau_{21})$ are the spontaneous emission rate and nonradiative relaxation rate, as shown in Fig.2. C_{up} is the upconversion coefficient, and K_{tr} and K_{ba} are the energy transfer and back-transfer coefficients respectively.

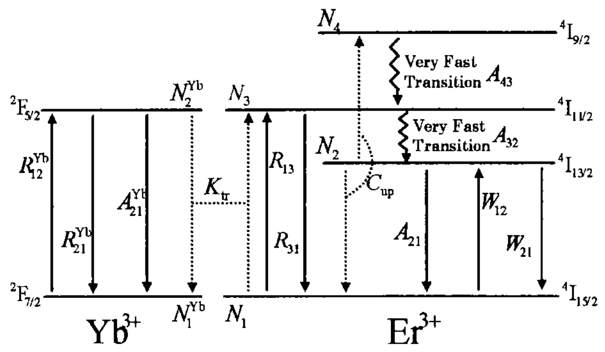

Fig. 2: Simplified energy diagram of the combined Er-Yb system.

Intensities can be shown for the propagation modes by, $I_i = p_i P_i$, where $p_i = \boldsymbol{E}_i \cdot \boldsymbol{E}_i^*$, $P_i = a_i \cdot a_i^*$. The stimulated emission and absorption rates are given by, $W_{12} = \frac{\sigma_{a12}}{h\nu_s}I_s$, $W_{21} = \frac{\sigma_{e21}}{h\nu_s}I_s$, $R_{13} = \frac{\sigma_{a13}}{h\nu_p}I_p$, $R_{31} = \frac{\sigma_{e31}}{h\nu_p}I_p$, $R_{12}^{Yb} = \frac{\sigma_{a12}^{Yb}}{h\nu_p}I_p$, $R_{21}^{Yb} = \frac{\sigma_{e21}^{Yb}}{h\nu_p}I_p$, where h is the Plank's constant, ν_s and ν_p are the signal and pump frequencies, σ_e and σ_a are the emission and absorption cross-sections respectively, and $I_s(x,y,z,t)$ and $I_p(x,y,z,t)$ are the signal and pump intensities, which can be written in terms of the corresponding normalized energy densities and power variations, $p(z)$ and $s(z)$, along the propagation direction [2], are given by,

$$I_p(x,y,z,t) = p(x,y)P_p(z,t) \quad \cdots\cdots (10)$$

$$I_s(x,y,z,t) = s(x,y)P_s(z,t) \quad \cdots\cdots (11)$$

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(x,y)dx\,dy = 1 \quad \cdots\cdots (12)$$

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} s(x,y)dx\,dy = 1 \quad \cdots\cdots (13)$$

$p(x,y)$ and $s(x,y)$ are the transverse pump and signal field distributions respectively. The variation of pump and signal intensities along the propagation direction are given by,

$$\frac{dP_p(z,t)}{dz} = -\left(\Gamma_p^{Er} + \Gamma_p^{Yb}\right)P_p(z,t) \quad \cdots\cdots (14)$$

$$\Gamma_p^{Er} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(x,y)(\sigma_{a13}N_1 - \sigma_{e31}N_3)dx\,dy$$

$$\Gamma_p^{Yb} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(x,y)(\sigma_{a12}^{Yb}N_1^{Yb} - \sigma_{e21}^{Yb}N_2^{Yb})dx\,dy$$

$$\frac{dP_s(z,t)}{dz} = (\Gamma_{12} - \Gamma_{21})P_s(z,t) \quad \cdots\cdots (15)$$

$$\Gamma_{12} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} s(x,y)\sigma_{a12}N_1 dx\ dy$$

$$\Gamma_{21} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} s(x,y)\sigma_{e21}N_2 dx\ dy$$

The integrations appeared in the Eqs.(14) and (15) must be performed over the region where the erbium/ytterbium doping is present, over the guiding region in the present case. For the calculation of steady-state response characteristics, cw signal with no variation with respect to time is used, and the derivatives appeared in Eqs.(2),(3) and (5)-(8) can be equated to zero. Equations (2)-(9),(14) and (15) were simultaneously solved numerically using forward difference Euler's method.

3. Steady-state Amplification Characteristics

For the analysis, we consider fundamental mode in the case of planar waveguide, and this approach is often used to analyze channel waveguides that are simplified to planar structures using effective index method [14]. The fabrication of this type of waveguides using RF sputtering method, and the optical characteristics are reported by one of the authors [1-4]. The experimental values of the parameters such as absorption and emission cross-section and lifetime of Er-ions are used for the calculations [1]. From the absorption and emission spectrum of the Er-doped thin film, the cross-sections are determined using the following commonly used Ladenburg-Fuchbauer (LF) relations [12,14].

$$\sigma_{e,a}(\lambda) = \frac{\lambda^4_{a,e,peak} I_{a,e}(\lambda)}{8\pi c n^2 \tau_{21}\int I_{a,e}(\lambda)d\lambda} \quad \cdots\cdots\cdots\cdots (16)$$

where $\lambda_{a,e,peak}$ is the wavelength at the absorption (emission) peak, τ_{21} is the lifetime of the upper laser level, n is the refractive index of the host medium, c is the velocity of light, and $I_{a,e}(\lambda)$ is the absorption or fluorescence spectrum. The pump absorption rates and signal emission rates for the case of Er-ions are given by the following relations.

$$R_{13} = \frac{\sigma_{a13}\lambda_p}{hc}\frac{P_p(0)}{A_{eff}}p(t,z) \quad (17)$$

$$R_{31} = \frac{\sigma_{e31}\lambda_p}{hc}\frac{P_p(0)}{A_{eff}}p(t,z) \quad \cdots\cdots\cdots (18)$$

$$W_{12} = \frac{\sigma_{a12}\lambda_s}{hc}\frac{P_s(0)}{A_{eff}}s(t,z) \quad \cdots\cdots\cdots (19)$$

$$W_{21} = \frac{\sigma_{e12}\lambda_s}{hc}\frac{P_s(0)}{A_{eff}}s(t,z) \quad \cdots\cdots\cdots (20)$$

Similar expressions can be written for the case of Yb-ions. In the above equations, $P_{p,s}(0)$ are the input pump and signal powers at $z = 0$ and A_{eff} is the effective area of the waveguide. The waveguide thickness is assumed to be $d = 1.5\ \mu m$ for which the waveguide is single moded at the signal wavelength, and the refractive index of the Er:YGG guiding region and YAG substrate are assumed to be 1.87 and 1.92 respectively, at the signal wavelength of 1.55 μm.

Table 1. Optical and spectroscopic parameters used for the numerical calculations.

Parameter	Value
Pump wavelength, λ_p	0.980 μm
Signal wavelength, λ_p	1.55 μm
Waveguide thickness, d	1.5 μm
Lifetime, τ_{21}	8.56 $msec$
Lifetime, τ_{32}	100 μsec
Lifetime, τ_{21}^{Yb}	2 $msec$
Pump absorption coefficient, σ_{a13}	$1.8 \times 10^{-24} m^2$
Emission coefficient, σ_{e12}	$3.25 \times 10^{-24} m^2$
Absorption coefficient σ_{a21}	$3.25 \times 10^{-24} m^2$
Yb absorption coefficient, σ_{a12}^{Yb}	$10.0 \times 10^{-24} m^2$
Yb emission coefficient, σ_{e21}^{Yb}	$10.0 \times 10^{-24} m^2$
Energy transfer coefficient, K_{tr}	$2.0 \times 10^{-22} m^3/sec$

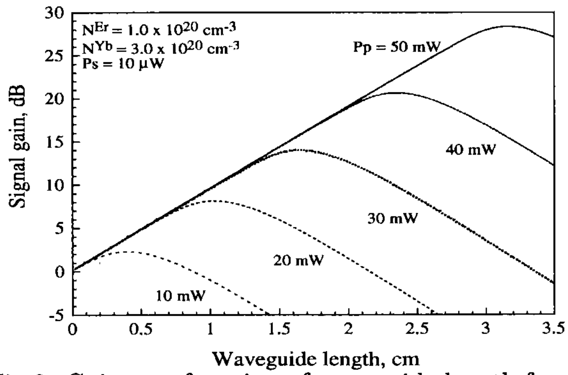

Fig.3: Gain as a function of waveguide length for different pump power in Er-Yb codoped amplifier.

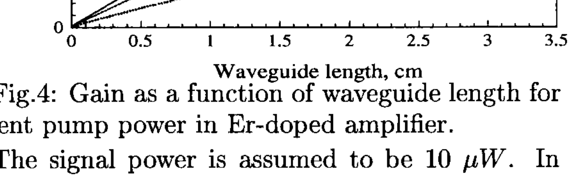

Fig.4: Gain as a function of waveguide length for different pump power in Er-doped amplifier.

The signal power is assumed to be 10 μW. In the case of Er-doped waveguides, either 980 nm or 1480 nm pump can be used. Yb-Er-codoped waveguide has the absorption peak around 980 nm Ref.[4,8], and 980 nm pumping has additional advantages over 1480 nm pumping such as lower pump threshold, higher source-to-waveguide coupling efficiency and lower noise characteristics [13]. In the numerical calculations, the width of the pump and signal beams are assumed to be 5 μm, and the up-conversion effect($^4I_{13/2} \rightarrow ^4 I_{9/2}$), and energy transfer back to the Yb-ions is neglected as the population N_3 of the Er^{3+} energy level is small as compared to other levels. The amplifier parameters assumed for the calculations are shown in Table 1. The experimental parameters of Er:YGG waveguides have been adopted from Ref [1], and since the experimental parameters for Yb-Er codoped waveguide fabricated using YGG host material were not available, the corresponding parameters of LiNbO3 are adopted from Ref.[8]. Using these parameters, calculations have been carried out to find the effect of amplifier parameters on the steady-state gain characteristics. The calculated variation of gain as a function of waveguide length for the cases of Er and Er-Yb are shown in Fig.3 and 4 respectively.

The interesting feature of Er-Yb codoped amplifier is that the length of the waveguide and pump power are critical factors for a desired gain. But, in the case of only Er-doped amplifier, the signal gain varies almost linearly till it reaches saturation for all pump powers. The result corresponding to only Er-doped amplifier agrees with our previous results [5]. A high gain of around 10 dB/cm can be obtained at the pump power of greater than 30 mW in the Er-Yb case. In the case of Er, a gain of 3-7 dB/cm in the pump power range of 30-50 mW. The gain variation is almost linear in the Er-doped case, whereas in the case of Er-Yb codoped case, the gain increases linearly in the beginning and drops drastically for all the pump levels. Also, from these figures, we can observe the fact that Er-Yb codoped amplifier yields better gain than the Er-doped amplifier.

The variation of gain in both the cases is illustrated in terms of the population density of upper laser level as shown in Figs.5 and 6. Similar observations were made for the case of varying Yb-ion concentration as shown in Fig.7. From these results one can find out the optimum Yb-ion concentration for a desired signal gain.

4. Dynamic Response Characteristics

The dynamic response of the amplifying medium is important when the input signal is modulated in various formats [15-19]. The analysis of transient response characteristics requires time integration of rate equations (Eqs.(1)-(8)) in addition to solving the length integration of the propagation equations (Eqs.(13),(14)). We employed a simple forward difference Euler's method [20] for the numerical calculations, similar to our earlier report [5]. The forward difference equations, for example, for the Er-ion population densities are,

$$N_1^{m,n+1} = N_1^{m,n} + \Delta t \frac{dN_1^{m,n}}{dt}$$

$$N_2^{m,n+1} = N_2^{m,n} + \Delta t \frac{dN_2^{m,n}}{dt} \qquad \cdots\cdots\cdots\cdots (21)$$

$$N_3^{m,n+1} = N_3^{m,n} + \Delta t \frac{dN_3^{m,n}}{dt}$$

and the difference equations for pump and signal beam are

$$P_p^{m+1,n} = P_p^{m,n} + \Delta z \frac{dP_p^{m,n}}{dz}$$

$$P_s^{m+1,n} = P_s^{m,n} + \Delta z \frac{dP_s^{m,n}}{dz} \qquad \cdots\cdots\cdots\cdots (22)$$

where, Δz and Δt are space and time steps. m and n are number of steps in the spatial and time coordinates. The initial conditions, at time t=0, are taken to be the steady state populations, $N_1^{m,0}$, $N_2^{m,0}$ and $N_3^{m,0}$ as explained at the end of Section 2.

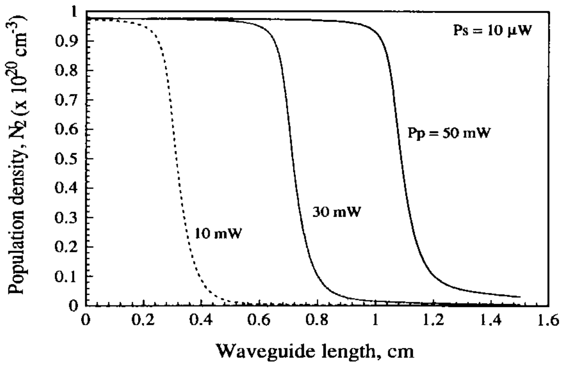

Fig.5: Population density of upper laser level in Er-Yb amplifier for different pump powers.

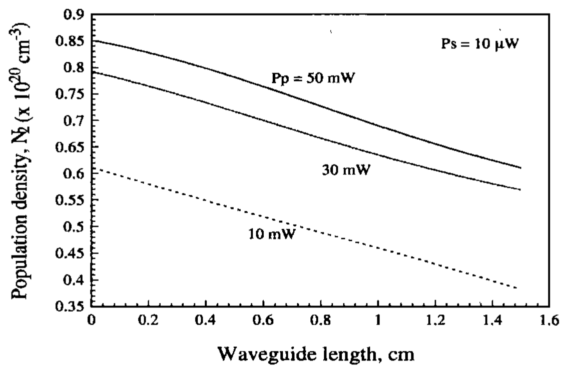

Fig.6: Population density of upper laser level in Er amplifier for different pump powers.

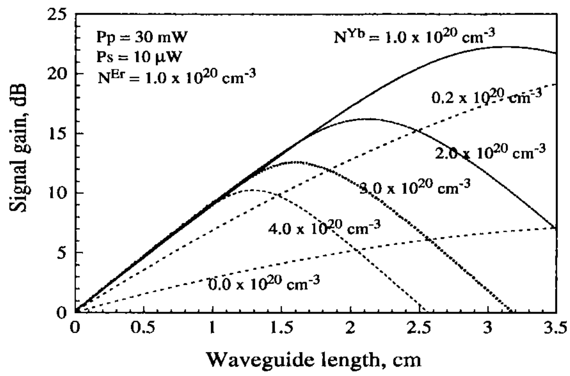

Fig.7: Effect of variation of Yb-ion concentration on the signal gain.

The square pulse propagation is first investigated. Fig.8,9 illustrate the shape of the output pulse intensity for different values of pump levels for the case of Er-Yb codoped and Er doped amplifier respectively. The signal pulse duration is assumed to be 100 μsec. In the calculations of Figs.8-12, waveguide length is assumed to be 5mm. As the pump intensity increases, the amplification becomes nonlinear, as in the bulk optics case

[15,16]. The effects in both the cases are found to be reversed. In the case of Er doped amplifier, the amplification of trailing edge of the pulse decreases because of depletion of population due to the leading edge. The upper laser level population in the Er-Yb waveguide amplifier, as can be observed from Figs.5, 6, is maintained at a higher level. In contrast with only Er-doped amplifier, the signal pulse will not experience appreciable change in the population during its propagation, and thus the pulse power increases with time. Pulses with varying pulse width have also been considered and the results are as shown in Figs.10,11. As expected, pulses with time duration of the order of excited level lifetimes are observed to be distorted. Very short pulses traverse through the amplifier before the upper laser level population depletes, resulting in less or no distortion upon amplification.

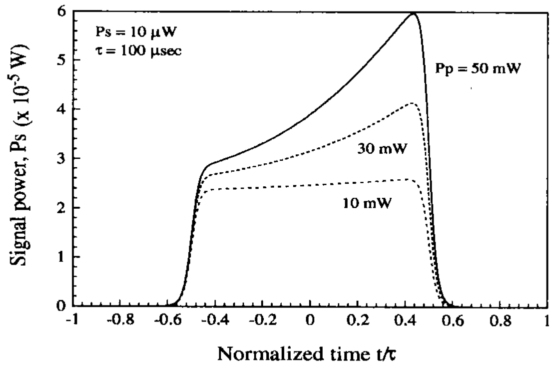

Fig.8: Square pulse amplification in Er-Yb case. The other parameters are shown in the figure.

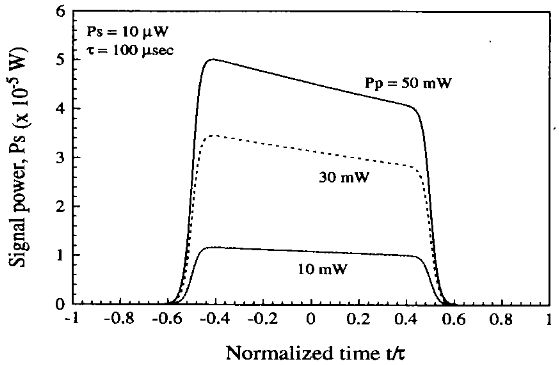

Fig.9: Square pulse amplification in Er case for different pump power levels.

Investigations were carried out for different input signal forms. One such case is shown in Fig.12, for the case of Gaussian input signal. For the reasons given earlier, pulses of longer duration get distorted, and for the present case, the peak of the pulse appears to be shifted to the right. This effect disappears for the shorter pulse duration.

5. Conclusions

In this paper, a waveguide amplifier using Yb-sensitized Er-doped Garnet crystals is proposed, and studies on steady state and transient amplification characteristics using time-dependent rate equations and propagation equations are presented. The potential of the amplifier operating at the present communication wavelength of 1.55 μm band is shown. A detailed comparison is made between Er-Yb and Er-doped cases, and the advantages of Yb-sensitization are shown.

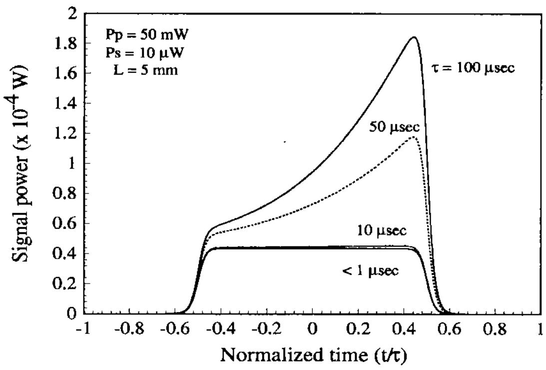

Fig.10: Effect of pulse duration on amplification in Er-Yb amplifier.

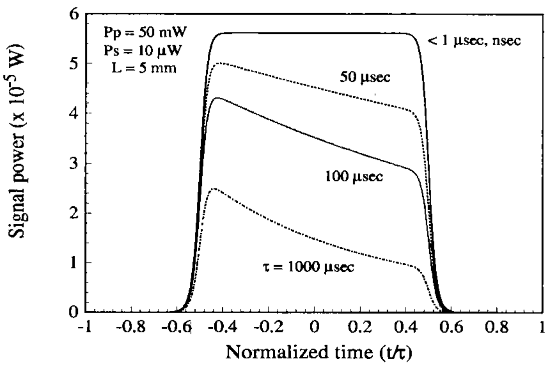

Fig.11: Effect of pulse duration on amplification in Er amplifier.

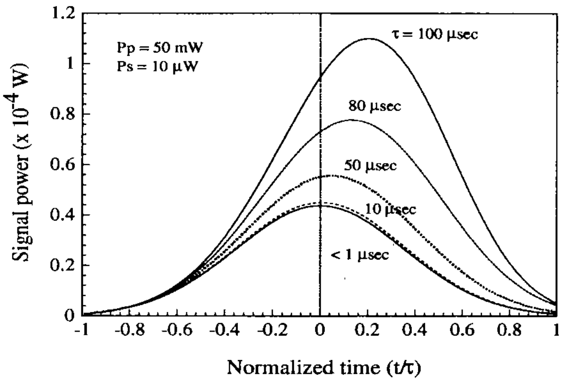

Fig.12: Gaussian pulse amplification in Er-Yb codoped amplifier.

The amplifier medium, particularly the population dynamics is shown to play an important role in pulse amplification. It is to be noted that the present analysis with rate equations is usful for the investigation of a single pulse propagating through the amplifying medium. Relatively large bandwidths, a measured value of around 20 nm for the Er-doped YGG waveguide amplifier, lead to distortionless amplification of ultrashort pulses. When the spectral bandwidth of pulses, with duration of the order of pico- and subpico-second, is comparable to the amplifier bandwidth, one can expect gain dispersion [21]. These cannot be included in the present simple rate equation formalism.

Practical realization of the proposed device is under progress. In order to estimate more accurate amplification properties, various amplifier parameters have to be determined experimentally. In the future, we have plans to determine these parameters experimentally and reexamine the amplification characteristics and compare the simulation results with the experimental results. Also, improved rate equations have to be developed for the studies of noise characteristics and ultra-short pulse propagation through the amplifier.

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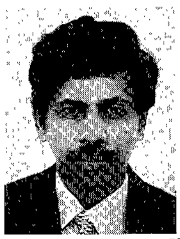

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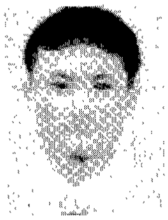

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