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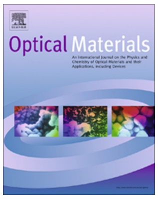

Gain and noise figure enhancement of Er^{+3}/Yb^{+3} co-doped fiber/Raman hybrid amplifier

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ABSTRACT

An Er/Yb co-doped fiber/Raman hybrid amplifier (HA) is proposed and studied theoretically and analytically to improve the gain and noise figure of optical amplifiers. The calculations are performed under a uniform dopant and steady-state conditions. The initial energy transfer efficiency for Er/Yb co-doped fiber amplifier (EYDFA) is introduced, while the amplified spontaneous emission (ASE) is neglected. The glass fiber used for both Er/Yb and Raman amplifiers is phosphate. Different pump powers are used for both EYDFA and RA with 1 μW input signal power, 1 m length of Er/Yb amplifier and 25 km length of Raman amplifier (RA). The proposed model is validated for Er/Yb co-doped amplifier and Raman amplifier separately by comparing the calculating results with the experimental data. A high gain and low noise figure at 200 mW Raman pump power and 500 mW Er/Yb pump power are obtained for the proposed HA as compared with the experimental results of EYDFA, Raman amplifier and the EDFA/Raman hybrid amplifier.

1. Introduction

Erbium doped fiber amplifier (EDFA) was studied in many researches to obtain large gain and low noise figure in the third window of optical fiber communications [1–3]. Other elements are introduced for different amplifiers which are co-doped with two rare-earth elements like erbium and ytterbium [4]. When Yb ions are co-doped with Er ions in the silica glass fiber glass or phosphate, a small Er-Yb ion-ion separation provides an indirect pump to erbium and increases the erbium concentration. This reduces the presence of Er clusters and the up-conversion rate from the upper level of erbium and so, a high gain is obtained from this co-doped fiber [5–8].

The nonlinear amplifiers, like distributed Raman amplifier, have a great important features in wavelength division multiplexing (WDM), long-haul, broadband transmission and ability to provide a flat gain profile in the optical communications. Many reports on Raman amplifications are present in recent years to display this features. T.J. Ellingham et al. investigated the effect of modulation instability in transmission in fibers to generate broadened laser pump spectra for two different pump wavelengths of Raman amplifier [9]. They demonstrated an extension of 0.1 dB continuous gain ripple bandwidth from 5 to 19 nm. Furthermore, in Ref. [10], the authors studied experimentally the full characterization of modern transmission fibers for Raman amplified based communication system and performed their experiment based on an averaged power analysis applied to a counter pumped long-haul distributed fiber Raman amplifier.

The hybrid amplifiers which are combinations of EDFA and RA have been demonstrated for many applications like higher transmission capacity on DWDM systems. This is because the nonlinear gain spectrum of RA in conjunction with saturation effects of EDFA causes an increase in signal power and decreases the optical signal-to-noise ratio [11–14]. S.H. Xu et al., measured the gain and noise figure of single mode highly Er/Yb co-doped phosphate with dual pump configuration at different values of input signal power. They obtained a net gain coefficient as high as 3.3 dB/cm from a micro EDFA based on a 5 cm long phosphate fiber [15].

L. Goldberg and J. Koplow worked on Er/Yb-co-doped compact fiber of length 3.5 m at a maximum pump power yielding a 47 dB small signal gain and 4.5 dB noise figure [16]. Other authors worked on hybrid amplifiers like Lee et al. who studied experimentally the characteristics of EDFA/Raman HA for three different types of pumping configurations and they obtained a net gain of 19 dB and a 6 dB noise figure at 1535 nm [17]. O. Mahran introduced an analytical study of a macro-bending EDFA/Raman HA. He found, due to bending loss in EDFA, that the gain of HA

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increased to ~7 dB when compared to the normal EDFA/Raman HA and that the noise figure decreased by ~2 dB rather than without macro-bending EDFA/Raman HA [18].

In this paper, a new HA is proposed which is a combination of two amplifiers; Er/Yb co-doped fiber amplifier of length 1 m and RA of length 25 km. Dual pumps are used; one forward at 980 nm with power of (100–500 mW) for the Er/Yb co-doped fiber and the other pump is backward at 1450 nm with power of (100–200 mW) for the RA and the input signal is 1 μW. The proposed model is validated for Er/Yb co-doped amplifier and Raman amplifier separately by comparing the calculated results with the experimental data of Refs. [16,10] respectively. The HA is proposed for improving the gain and noise figure. The most important applications of such HA are: i – high transmission capacity DWDM, ii – common antenna television, iii – free space communications and iv – long wavelength L- C band amplifier.

2. Theory

The system of the proposed HA is shown in Fig. 1, where the input signal for the first amplifier, EYDFA, $P_{s1}(0)$ which is amplified to $P_{s1}(L)$ is considered as an input signal, $P_{s2}(0)$ for the second amplifier (RA), i.e., $P_{s1}(L) = P_{s2}(0)$. The final output signal will be $P_{s2}(L_R)$ and the net gain of HA is the ratio between $P_{s2}(L_R)$ and $P_{s1}(0)$, where L is the EYDFA length and L_R is the RA length.

To calculate $P_{s1}(L)$, we start with the energy levels system of EYDFA as shown in Fig. 2. The energy levels of Er^{+3} are E_1, E_2 and E_3 corresponding to ($^4\mathrm{I}_{15/2}$, $^4\mathrm{I}_{13/2}$ and $^4\mathrm{I}_{11/2}$), respectively, and the energy levels of Yb^{+3} are E_4 and E_5 corresponding to ($^2\mathrm{F}_{7/2}$, $^{2\mathrm{F}}\mathrm{I}_{5/2}$), respectively. When the 980 nm pump power activates the Yb^{+3} ions, N_4 at E_4 absorbs the pump energy and transits up to E_5, where the number of Yb^{+3} ions is N_5. Then, the energy transfers rapidly to E_1 of the Er^{+3}. This energy makes the Er ions (N_1) excited from level E_1 to the level E_3 (N_3) which rapidly decays to the metastable level E_2 of the Er^{+3}. Now, the number of Er^{+3} ions N_2 at E_2 becomes larger than the number of Er^{+3} ions N_1 at E_1 (population inversion) and amplification process of the signal occurs.

The number of Er^{+3} N3 is small and can be neglected, so we can write [19–22]

$$N_1(z) + N_2(z) = N_{\mathrm{Er}}$$

and

$$N_4(z) + N_5(z) = N_{\mathrm{Yb}}$$

where z is the length of the EYDFA, N_{Er} is the erbium concentration and N_{Yb} is the ytterbium concentration.

Under uniform dopant and steady-state conditions, one can write the rate equations as [19–21]

$$\frac{N_2}{\tau_{21}} - \varepsilon_{12}N_1 + \varepsilon_{21}N_2 - \vartheta_{13}N_1 = 0 \tag{1}$$

$$\frac{N_5}{\tau_{54}} - \vartheta_{45}N_4 + \vartheta_{54}N_5 = 0 \tag{2}$$

with

$$\frac{N_2}{N_2 + N_5} = \mu_o \text{ or } N_5 = \frac{1-\mu_o}{\mu_o}N_2 \tag{3}$$

where ε_{ij}, ϑ_{ij} are, respectively, the transition rates for Yb and Er ions, τ_{ij} are the decay rates for Yb and Er ions and μ_o is the initial energy transfer efficiency.

$$\varepsilon_{12} = \frac{\sigma_{12}(\upsilon_p)P_p(z)\Gamma_p}{A_{eff}h\upsilon_p},\ \varepsilon_{21} = \frac{\sigma_{21}(\upsilon_s)P_s(z)\Gamma_s}{A_{eff}h\upsilon_s},\ \vartheta_{13} = \frac{\sigma_{13}(\upsilon_p)P_p(z)\Gamma_p}{A_{eff}h\upsilon_p},$$
$$\vartheta_{45} = \frac{\sigma_{45}(\upsilon_p)P_p(z)\Gamma_p}{A_{eff}h\upsilon_p} \text{ and } \vartheta_{54} = \frac{\sigma_{54}(\upsilon_p)P_p(z)\Gamma_p}{A_{eff}h\upsilon_p} \tag{4}$$

where Γ_p and Γ_s are, respectively, the overlapping factors of the pump and the signal, A_{eff} is the cross-sectional area of the amplifier, $\sigma_{12}(\nu_s)$ and $\sigma_{21}(\nu_s)$ are the signal absorption and emission cross-sections, 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-sections, respectively, and h is Planck's constant.

Solving Eqs. (1)–(3), one obtains

$$N_1 = \frac{\left(\frac{1}{\tau_{21}} + \varepsilon_{21}\right)}{(\varepsilon_{12} + \vartheta_{13})}N_2 \tag{5}$$

$$N_4 = \frac{\left(\frac{1}{\tau_{54}} + \vartheta_{54}\right)}{\vartheta_{45}}.\frac{(1-\mu_o)}{\mu_o}N_2 \tag{6}$$

Assuming P_p and P_s being the pump and signal powers, respectively, in the steady state, the pump and signal powers can be written as [19]

$$\frac{dP_p(z)}{dz} = -\Gamma_p[\sigma_{13}(\nu_p)N_1(z) + \sigma_{45}(\nu_p)N_4(z) - \sigma_{54}(\nu_p)N_5(z)]P_p(z) \tag{7}$$

$$\frac{dP_s(z)}{dz} = \Gamma_s[\sigma_{21}(\nu_s)N_2(z) - \sigma_{12}(\nu_s)N_1(z)]P_s(z) \tag{8}$$

Using Eqs. (3), (5), (6) in Eqs. (7), (8), one gets

$$\frac{dP_p(z)}{P_p(z)} = -\Gamma_p\left[\sigma_{13}\frac{\left(\frac{1}{\tau_{21}} + \varepsilon_{21}\right)}{(\varepsilon_{12} + \vartheta_{13})} + \sigma_{45}\frac{\left(\frac{1}{\tau_{54}} + \vartheta_{54}\right)}{\vartheta_{45}}\frac{1-\mu_o}{\mu_o} - \sigma_{54}\frac{1-\mu_o}{\mu_o}\right]$$
$$\times N_2(z)dz \tag{9}$$

$$\frac{dP_s(z)}{P_s(z)} = \Gamma_s\left[\sigma_{21} - \sigma_{12}\frac{\left(\frac{1}{\tau_{21}} + \varepsilon_{21}\right)}{(\varepsilon_{12} + \vartheta_{13})}\right]N_2(z)dz \tag{10}$$

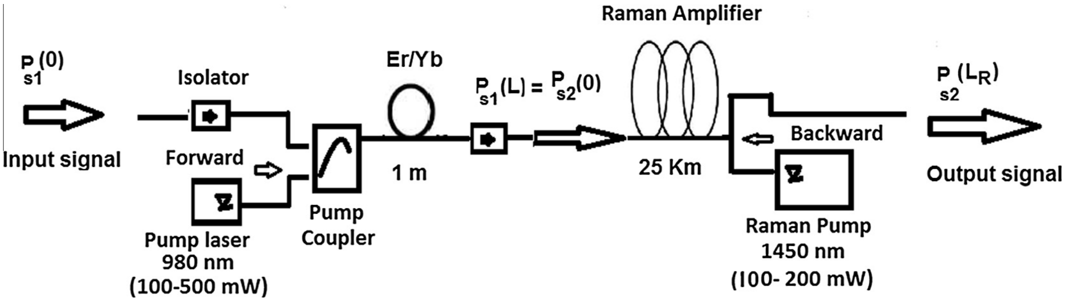

Fig. 1. System of EYDFA/RA hybrid optical amplifier.