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Consideration Spectroscopy Characterization and Influence of Cooperative Up-Conversion in Erbium Doped Ta_2o_5 Trapezoid Waveguide Amplifier

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Abstract:
We report the design and simulation of spectroscopic characteristics and gain of erbium doped Ta_2O_5 trapezoid waveguide amplifier. Guiding modes, field distribution are calculated. Percentage of core power at wavelength of 1.53µm, 0.98µm and overlap factor studied. Based on rate equation, influence of cooperative up-conversion on gain with consideration to different parameters is numerically calculated.

Keywords:
Erbium, Gain, Tantalum pentoxide, Waveguide amplifier.

I. Introduction

Erbium doped waveguide amplifiers (EDWA) are key components in optical telecommunications. EDWA can provide high gain and in a variety of hosts have been developed rapidly. Especially Ta_2O_5 waveguide amplifiers on SiO_2 substrate have attracted considerable attention. Ta_2O_5 is chosen as host material of erbium, which is a high refractive index material and having a refractive index greater than 2[i]. On the other hand high confinement can be realized with large refractive index changes between Ta_2O_5 and SiO_2. Tantalum pentoxide had high radiative efficiency and a large third order non-linearity [ii,iii]. A high refractive index contrast material allows strong confinement of light. Optical amplifiers have low propagation losses. Optical measurements were calculated yield the waveguide attenuation and erbium absorption and emission cross-section. Spectroscopy and performance of erbium doped Ta_2O_5 rectangular waveguide amplifiers were calculated [iv]. In this paper we report the characteristics of erbium doped Ta_2O_5 trapezoid waveguide amplifier. We analyze the influence of etched cross-section on guiding modes, field distribution, mode intensity and overlap factor between signal and pump wavelengths.
Finally we calculated gain of waveguide amplifier and represented effect of cooperative up-conversion.

II. Experimental procedures

In this article trapezoid waveguide amplifier is considered with width of w_1=2µm, w_2=0.4µm, rib height h=1µm and etch depth of D=0.3µm, as shown in Fig. 1(a). The refractive index of core and cladding are 2.1 and 1.44 respectively.

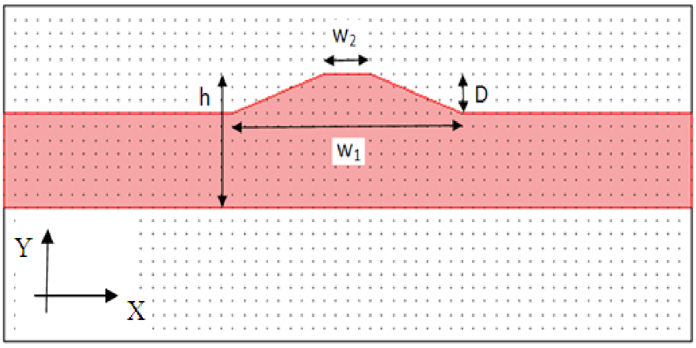
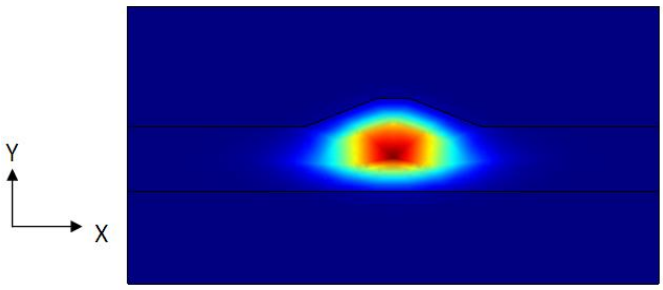
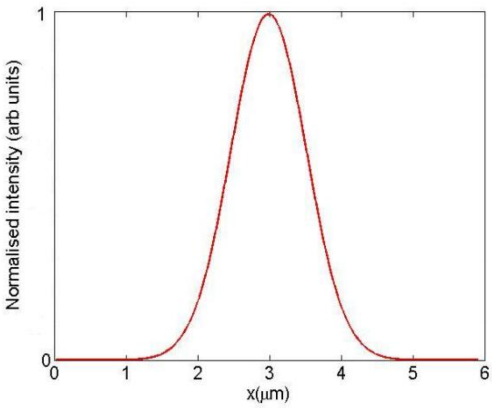


Fig. 1. Schematic diagram of the rib trapezoid waveguide with dimension of w_1=2µm, w_2=0.4µm, D=0.3µm and h=1µm.

Guiding modes and field distribution and intensity of the mode overlap factor with the active region in the above waveguide are analyzed by COMSOL Multiphysic Software for the signal(1530nm) and pump(980nm) wavelengths shown in fig 2.



(a)



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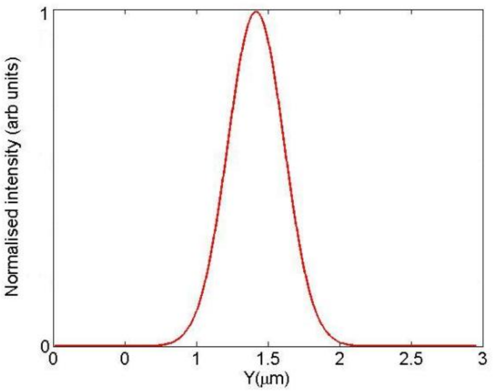


(b)

Fig. 2: (a) Simulation of mode profile for the trapezoid waveguide at signal and pump wavelengths. (b) Mode intensity profile in the x and y directions.

Table.1: Parameter used in the simulation of signal gain [iv].

parameter	value
(σ_{12})signal absorption cross 1527nm section at	**4.8×10^{-21} cm^2**
(σ_{21})signal emission cross section 1527nm at	**4.4×10^{-21} cm^2**
(σ_{13})pump absorption cross section 977nm at	**2.1×10^{-21} cm^2**
(σ_{31})pump emission cross section at 977nm	**0 cm^2**
(τ_{21})lifetime $I_{13/2}$	**2.3 ms**
(τ_{32})lifetime $I_{11/2}$	**30 µs**
(α_p)waveguide loss at pump wavelength	**0.23 cm^{-1}**
(α_s) waveguide loss at signal wavelength	**0.15 cm^{-1}**
(Γ_s)overlap factor	**0.98**
(Γ_p)overlap factor	**0.9**
(C_{up})cooperative up-conversion coefficient	**0 – 10^{-17} cm^3/s**

II. Results and discussion

Gain measurements were performed by solving the rate equations for the erbium ions in a three-level erbium ion system with the pump and signal evolution along the length of the waveguide in MATLAB software. If n_1, n_2 and n_3 be the fraction of population of the erbium ions and N_t be the total erbium concentration, then the following can be written

$$\frac{dn_1}{dt} = -W_{13}n_1 + W_{21}n_2 - W_{12}n_1 + \frac{n_2}{\tau_{21}} + N_tC_{up}n_2^2 \quad (1)$$

$$\frac{dn_2}{dt} = W_{12}n_1 - W_{21}n_2 - \frac{n_2}{\tau_{21}} - 2N_tC_{up}n_2^2 + \frac{n_3}{\tau_{32}} \quad (2)$$

$$\frac{dn_3}{dt} = W_{13}n_1 + N_tC_{up}n_2^2 + \frac{n_3}{\tau_{32}} \quad (3)$$

$$W_{ij} = \frac{I_{p,s}\sigma_{i,j}^{p,s}}{h\nu_{p,s}} \quad (4)$$

In this equations, the W_{ij} terms represent the stimulated transition rates between the i and j levels. $I_{p,s}$ is the pump and signal intensities. The evolution of signal and pump powers along the propagation direction is governed by the following differential equations:

$$\frac{dp_p(z)}{dz} = \left(-\alpha_p + \left(\sigma_{31}n_3(z) - \sigma_{13}n_1(z)\right)\Gamma_p N_t\right)P_p(z,\nu_p) \quad (5)$$

$$\frac{dp_s(z)}{dz} = \left(-\alpha_s + \left(\sigma_{21}n_2(z) - \sigma_{12}n_1(z)\right)\Gamma_s N_t\right)P_s(z,\nu_s) \quad (6)$$

$$G(z)=(dP_s/dz)/P_s(z)=(-\alpha_s+(\sigma_{21}n_2(z)-\sigma_{12}n_1(z))\Gamma_sN_t) \quad (7)$$

G(z) is the gain of the amplifier. The parameters used for evaluate the gain are shown in **Table 1**.

Fig 3 shows the effect of up-conversion on the gain along the length of the waveguide at constant pump power 200 mW and erbium concentration $N_t= 2\times10^{20}$ ions/cm^3, and different C_{up}. At 200 mW with no up-conversion, a high level of inversion is achieved. leading to higher gain (28 dB) over the length of 10cm as shown by the blue line in Fig 3. At $C_{up}=1\times10^{-18}$ cm^3/s and $C_{up}=1\times10^{-17}$ cm^3/s gain is reduced to 27dB and 21dB respectively.

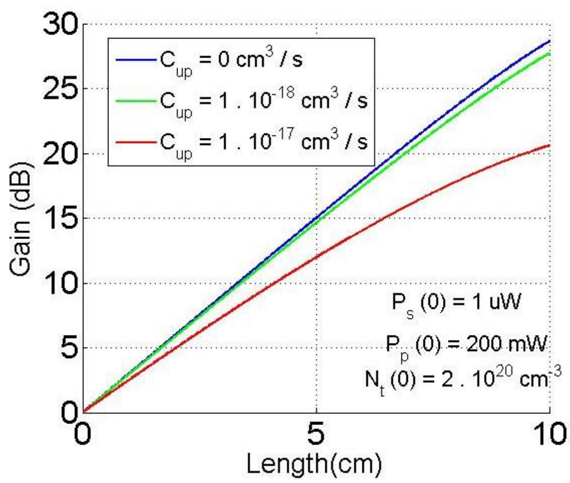
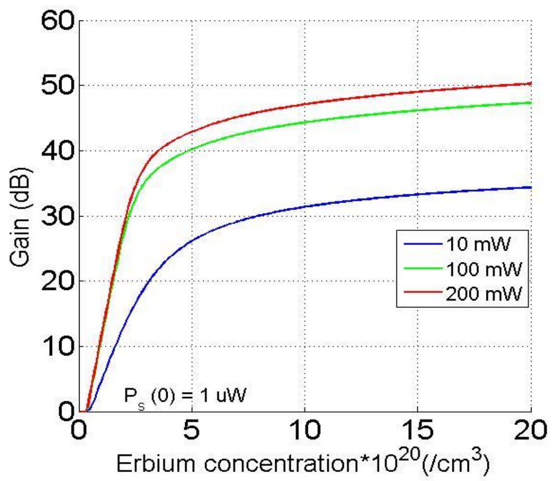
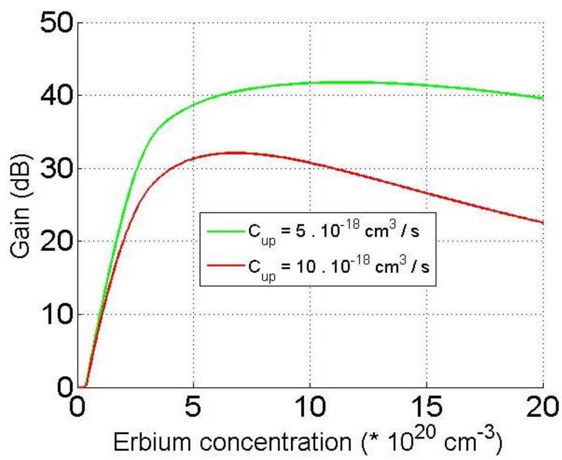


Fig. 3. variation of signal gain along the length of the trapezoid waveguide for fixed erbium concentration, pump and signal power and various up-conversion coefficients.

Fig.4(a, b) shows the gain as a function of erbium concentration with and without up-conversion. This gain was plotted against the erbium concentration at different pump power (10, 100, 200mW) as shown in Fig. 4a. It can be seen from this plot that there does not exist any optimum concentration for any of the three pump powers for maximizing the signal gain from the amplifier. This is because the up-conversion factor has not been taken into account resulting in the increase in the gain with the erbium concentration. Optimum power pump achieved 200mW. In Fig. 4b, the same result is plotted with different C_{up} and the effect of up-conversion can be immediately seen as there is an optimum concentration for achieving maximum gain, at fixed 200mW pump and 1µW signal power.



(a)



(b)

Fig. 4. Signal gain variation for different erbium concentrations. (a) without up-conversion(C_{up}=0) and various pump power(10, 100, 200mW).(b) for C_{up} =5×10^{-18} cm^3/s, C_{up} =10×10^{-18} cm^3/s at optimum pump power 200mW.

This result presented in Fig. 4 is the last and the most important of the performance maps for extracting the optimum performance from the EDWA. The results can be used to predict the erbium concentration and the length of the waveguide for a given pump power and up-conversion coefficient that should be used to extract maximum gain from the amplifier. For $Er:Ta_2O_5$, for a pump power of 200mW, and signal power of 1 μW, the maximum gain that can be extracted is summarized in Table 2 and is extracted from Fig. 4b. A maximum gain of 43 dB can be achieved at erbium concentration 10×10^{20} ions/cm^3 and C_{up}=5×10^{-18} cm^3/s. For a very high value of C_{up}=10×10^{-18} cm^3/s, the gain reduces to 33 dB at a reduced concentration of 7×10^{20} ions/cm^3.

Table.2: Maximum gain achievable in $Er:Ta_2O_5$ for a pump power of 200mW for different cooperative up-conversion. coefficient.

C_{up} (cm^3/s)	N_t (ions/cm^3)	Gain(dB)
5×10^{-18}	10×10^{20}	43
10×10^{-18}	7×10^{20}	33

III. Conclusion

The trapezoid waveguide designed in order to obtain higher gain performance and ensure single mode operation at the signal and pump wavelength. Spectroscopic characteristics of waveguide amplifiers are discussed. Reaches well confinement of the electromagnetic field and high overlap factor on the condition of ensuring single mode operation at the signal and pump wavelength. The effect of different up-conversion has been taken into account and its effect on the gain of the system has been represented. The equations were solved numerically and the evolution of signal, pump and gain were obtained by solving the rate equation at each length interval. The signal gain characteristics were analysed as a function of length of the waveguide and erbium concentration.

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