Performance Evaluation of Short Wavelength Gain of A Thulium-Doped Tantalum Pentoxide Waveguide

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Research Article

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Abstract

In this study, the design of a thulium-doped Ta_2O_5 amplifier is promoted for amplification at $1.72\text{ }\mu\text{m}$. The width of the rib waveguide is theoretically optimized to achieve single mode guidance. The finite element method is used to compute the main optical characteristics such as effective mode field area and the waveguide confinement factor. The theoretical model based on the rate and propagation equations is built up to study the amplification performance of the Tm doped Ta_2O_5 amplifier. The waveguide length and pump power are investigated through the analytical analysis to achieve a high performance amplifier at $1.72\text{ }\mu\text{m}$. The obtained results support that thulium-doped Ta_2O_5 is a good way to realize an efficient amplifier and laser source at $1.7\text{ }\mu\text{m}$ waveband.

1. Introduction

In recent years, particular interest has been devoted to demonstrate the $1.7\text{ }\mu\text{m}$ band due to its unique spectroscopic characteristics. This band has many absorption peaks such as fat, water molecules and S-H bands, so it is widely used in applications of medical treatments, materials processing and gas detection [1–3]. Moreover, this wavelength region is also used as a pump wavelength for Dy^{3+} -doped chalcogenide and fluoridate fiber laser at $4.5\text{ }\mu\text{m}$. The $1.7\text{ }\mu\text{m}$ waveband can be generated with a Raman fiber laser pumped at $1.5\text{ }\mu\text{m}$ [4] and an optical parametric oscillator [5]. However, the first candidate required a long Raman fiber length to achieve sufficient gain, while a high nonlinear fiber with complicated configuration is required for the second source [6]. Another way to achieve the $1.7\text{ }\mu\text{m}$ region light sources is by rare earth doped fibers such as a thulium doped silica fiber. Although, thulium silica has a broad emission band across 1650nm to 2100nm , there are challenges to achieve powerful laser operation at short wavebands of thulium emission. This is due to serious-wavelength amplified spontaneous emission and strong re-absorption [7].

In order to realize a highly compact fiber source and amplifier at the $1.7\text{ }\mu\text{m}$ waveband, a thulium doped tantalum pentoxide waveguide $\text{Tm}:\text{Ta}_2\text{O}_5$ is suggested to use due to its higher emission cross section at short wavelength than that in thulium doped silica host material [8]. In comparison with other host material, tantalum pentoxide exhibits a high refractive index, low quenching, high solubility, low phonon energy, high nonlinearity and Raman gain, widely emission spectrum between 300nm to 9000nm . Furthermore, Ta_2O_5 is compatible with silicon and silicon dioxide technology due to its good mechanical and thermal properties [9]. This excellent compatibility makes Ta_2O_5 a promising host material for rare earth ions in future systems [10]. Ta_2O_5 has been initially demonstrated for neodymium as a good host material and laser [11], the propagation losses of this waveguide at $1.07\text{ }\mu\text{m}$ were about 2dB/cm . Later, the luminescence properties of erbium doped Ta_2O_5 have been studied when pumped with a laser diode at 977 nm , the measured propagation losses were 0.65dB/cm , while the optical gain at 1531nm was 2.1dB/cm [9]. Ta_2O_5 was also realized for ytterbium, the propagation losses has been improved to less 0.2dB/cm and the measured output power was 25mW at 1025nm with 27% of slop efficiency [12]. Recently, Tm- doped Ta_2O_5 waveguide has been demonstrated for emission around $2\text{ }\mu\text{m}$ wavelengths.

The optical characteristics of this waveguide described that the emission cross section of Ta₂O₅ is significantly higher than that in silica host glasses with a peak at 1772nm which is located toward the short wavelength [8].

Here in this study, the design of a Tm doped Ta₂O₅ amplifier is promoted for amplification at 1.72 μm. Firstly, the width of the waveguide is theoretically optimized to achieve a single mode operation of the waveguide. Then our own finite element method is applied to calculate the effective mode field area and the waveguide confinement factor. The waveguide parameters such as waveguide length and pump power are investigated through the analytical analysis to achieve a high performance amplifier at 1.72 μm. The obtained results support that Tm:Ta₂O₅ is a good way to realize a good amplifier and laser source at 1.7 μm waveband.

2. Waveguide Design

Achieving single mode operation is a pre-requisite for most planar lightwave devices. In the case of high index materials for instant SiO₂ and Ta₂O₅, a submicron range of the transverse dimensions of the rectangular waveguide is required for realizing single mode condition [13]. This requirement reduces the coupling efficiency and makes the fabrication tolerances under extra pressure. Thus, the rib waveguide is used to enhance the optical coupling with relaxed fabrication tolerances whilst the single mode condition is maintained with large dimensions [9]. Figure 1 presents the structure of the rib waveguide which consists of two different materials. The top and down cladding layers are SiO₂ whilst the middle core layer is Tm:Ta₂O₅.

Figure (1). Schematic diagram of the rib waveguide.

At large cross section of the rib waveguide, the single mode condition is achieved by [14]:

$$r > 0.5$$

1

$$t \leq \frac{r}{\sqrt{1-r^2}} + C$$

2

$$t = \frac{W}{H}$$

3

Where $r = h/H$, W is the waveguide width, H and h are the rib and slab height of the waveguide, respectively whilst d is the etch depth ($d=H-h$). The constant parameter C in Eq. (2) is equal to 0.3

according to the Soref approach [14]. To optimize the waveguide design under single mode guidance, the waveguide dimensions are fixed as following: etch depth (d)=400nm, rib height (H)=2μm, slab height (h=H-d=1600nm) whilst the waveguide width (W) is varied between 0 to 5 μm. The calculated value of parameter (t) from Eq. (3) must be under the condition of Eq. (2) to ensure single mode operation. Figures (2) shows the calculated of (t) parameter with variation of (W) dimension. It is clearly notice that the width of the waveguide must be less than 3.2μm to ensure single mode guidance.

After optimization of the waveguide dimensions, now the main optical characteristics such as the overlapping factor and the effective mode filed area can be computed by applying our FEM software [15, 16]. Firstly, the electric field distribution of the fundamental mode is computed then the overlapping factor and effective mode filed area are calculated according to the following relations:

$$\Gamma = \frac{\iint_{core} |E^2(x, y)| dx dy}{\iint_{-\infty}^{\infty} |E^2(x, y)| dx dy}$$

4

$$A_{eff} = \frac{\iint_{-\infty}^{\infty} (|E(x, y)|^2 dx dy)^2}{\iint_{-\infty}^{\infty} |E(x, y)|^4 dx dy}$$

5

where E is the electric field of the fundamental mode. Figures (3) illustrates the distribution of the electric field norm of the fundamental mode at the wavelength 1720nm. The confinement of optical field is clearly maintained inside the core layer. According to equations 4 and 5 with choosing the waveguide width at 3μm, the calculated values of overlapping factor and effective mode field area at the wavelength 1720nm are 0.83 and 6.8 μm², respectively.

Figure (2). Optimum value of W dimension to ensure single mode condition.

Figure (3). The distribution of electric field norm for the fundamental mode at 1720nm.

3. Modelling Of The Amplifier

The theoretical model of the amplification process is based on the interaction of thulium ions with the pump and signal power with existence of amplified signal emission ASE light [17]. This interaction is described by solving the atomic rate equations of thulium ions in a two-energy levels system as illustrated in figure (4). In this model, the effects of up conversion and cross relaxation processes are not considered.

Figure (4) simplified diagram of thulium ions.

The rate equations of a thulium doped fiber pumped at 1630nm can be written [18]:

$$\frac{dn_2}{dt} = w_{p12}n_1 - w_{p21}n_2 - \frac{n_2}{\tau_2} - w_{21}n_2 + w_{12}n_1$$

6

$$n_1 = n_{th} - n_2$$

7

Where n_{th} is the total thulium concentration, n_1 is the population density of the thulium ions at 3H_6 level, n_2 is the population density of the thulium ions at 3F_4 level, τ_2 is the lifetime of level 3F_4 . The expression of pump rate (w_{p12}), the de-excitation rate (w_{p21}), the stimulated emission rate (w_{21}) and the absorption rate (w_{12}) are given by [19]:

$$w_{p12} = \frac{\lambda_p \sigma_{p12}}{h c A_{eff}} n_1 p_p$$

8

$$w_{s12} = \frac{\lambda_s \sigma_{s12}}{h c A_{eff}} n_1 (p_s + ASE^+ + ASE^-)$$

9

where i and j correspond the first and second energy levels of thulium ions, respectively. p_p and p_s are the pump and signal powers, respectively. ASE^+ and ASE^- are the forward and backward ASE powers, respectively. σ_{p12} is the corresponding absorption and emission cross section at the pump wavelength while σ_{s12} is the corresponding absorption and emission cross section at the signal wavelength. The power distributions of the pump, signal and ASE along the thulium length are given by [19, 20]:

$$\frac{dp_p}{dz} = - (\alpha_p + \sigma_{p12} n_1) p_p$$

10

$$\frac{dp_s}{dz} = (\sigma_{s12} n_1 - \sigma_{s21} n_2 - \alpha_s) p_s$$

11

$$\begin{aligned}\frac{dASE^+}{dz} = & ASE^+ \left(\sigma_s \sigma_{s10} n_2 - \sigma_s \sigma_{s01} n_1 \right) \\ & + 2\sigma_{s10} n_2 \frac{hc^2}{\lambda_s^3} \Delta\lambda_s - \alpha_s ASE^+\end{aligned}$$

12

$$\begin{aligned}\frac{dASE^-}{dz} = & -ASE^- \left(\sigma_s \sigma_{s10} n_2 - \sigma_s \sigma_{s01} n_1 \right) \\ & - 2\sigma_{s10} n_2 \frac{hc^2}{\lambda_s^3} \Delta\lambda_s + \alpha_s ASE^-\end{aligned}$$

13

where the propagation losses of the pump and signal wavelengths inside the waveguide are termed as α_p and α_s , respectively.

4. Simulation Results

After optimization of the rib waveguide geometry, now, the amplification process can be described by solving analytically the thulium rate equations in conjunction with the distribution of the pump, signal and ASE powers along the waveguide length. At the steady condition, the time derivatives of equations (6) should be set to zero to compute the population densities of thulium energy levels. Then, Runge-Kutta method with the relaxation algorithm is applied to solve the differential equations (10)-(13) for the distributions of the pump, signal and ASE powers along the thulium length.

Table (1) lists all required parameters for the analytical simulations. The absorption and emission cross-section spectra for the Tm:T₂O₃ is shown in figure (7) [9]. This figure indicates that the peak emission cross section is $5.7 \times 10^{-21} \text{ cm}^2$ at the wavelength 1772nm which is higher than that in similar doped silica host material.

Table 1
The required fiber parameters used in the analytical model [9].

Symbol	Explanation	Value
N_{th}	Thulium concentration	$1.1 \times 10^{27} \text{ m}^{-3}$.
λ_s	Signal wavelength	1720nm.
λ_p	Pump wavelength	1630nm.
$\Gamma_{p,s}$	Overlap factor for pump and signal	0.83.
W	Waveguide width	2 μm .
H	Waveguide height	2 μm .
D	Waveguide etch depth	400nm.
$\alpha_{p,s}$	Waveguide loss at pump and signal	0.65dB.
λ_p	Pump wavelength	1950nm.
λ_s	Signal wavelength	2090nm.
σ_{p01}	Absorption cross section at the pump wavelength	$3 \times 10^{-25} \text{ m}^2$.
σ_{p10}	Emission cross section at the pump wavelength	$1.25 \times 10^{-25} \text{ m}^2$.
σ_{s01}	Absorption cross section at the pump wavelength	$3.8 \times 10^{-25} \text{ m}^2$.
σ_{s10}	Emission cross section at the signal wavelength	$4.65 \times 10^{-2} \text{ m}^{-1}$.
τ_2	3F_4 Lifetime	477 μs .

Figure (5). Holmium absorption and emission cross-sections.

Firstly, the optimum thulium fiber length is evaluated at 1630nm pump wavelength. At these simulations, a pump power of 100mW is launched via a forward pump configuration whilst the seed power is 0.1mW at a wavelength of 1720nm. Figures (6) shows the obtained gain as a function of the length of the rib waveguide. The results indicate that, the gain is increased along the waveguide until reach its maximum value at length 6cm. The distributions of the pump power and signal power along the waveguide are shown in figure (7) whilst figure (8) illustrates the distribution of the forward and backward ASE power versus the waveguide length. The above results indicate that only 100mW is capable to deliver more than 25 dB small signal gain and 8.7dB noise figure at the wavelength of 1720nm. This large value of noise figure is due to a big ASE power in forward and backward directions as shown in figure (8). It is possible to restrict this value of ASE signal via using ASE filtering.

Figure (6). The obtained gain of Tm:T₂O₃ versus length of the rib waveguide.

Figure (7). The distributed pump and signal powers along the waveguide.

Figure (8). The distributions of forward and backward powers along the waveguide.

The last investigation is to evaluate the dependence of the amplifier gain with the pump power.

Figure (9) indicates the effect of the pump power on the maximum signal gain. At this investigation, the adjustment of the waveguide length is performed at every pump power value to provide the maximum gain whilst the other parameters are fixed. It is clearly observed that the gain start increasing significantly with increase of the pump power until its value of 130mW which the growth becomes slightly.

Figure (9). The variation of the signal gain with the launched pump power.

5. Conclusions

In comparison with other materials, tantalum pentoxide exhibits a high refractive index, low quenching, high solubility, low phonon energy and widely emission spectrum between 300nm to 9000nm. In order to realize a highly compact fiber source and amplifier at the 1.7 μm waveband, a Tm:Ta₂O₅ waveguide is suggested to use due to its higher emission cross section at short wavelength than that in thulium doped silica host material. Here in this study, the design of a Tm doped Ta₂O₅ amplifier is promoted for amplification at 1.72 μm . Firstly, the width of the waveguide is theoretically optimized to achieve a single mode operation of the waveguide. Then our own finite element method is applied to calculate the effective mode field area and the waveguide confinement factor. The waveguide parameters such as waveguide length and pump power are investigated through the analytical analysis to achieve a high performance amplifier at 1.72 μm .

The obtained results showed that the width of the waveguide must be less than 3.2 μm to ensure single mode guidance. The calculated values of the overlapping factor and the effective mode field area at the wavelength 1720nm and ($W = 3\mu\text{m}$) are 0.83 and 5.4 μm^2 , respectively. In the amplifier performance, only 100mW of pump power is capable to deliver more than 25 dB small signal gain and 8.7dB noise figure at the wavelength of 1720nm, whilst using in-band pumped configuration. As a result, Tm:Ta₂O₃ is a good way to realize an efficient amplifier and laser source at the 1.7 μm waveband.

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Figures

Figure 1

Schematic diagram of the rib waveguide.

Figure 2

Optimum value of W dimension to ensure single mode condition.

Figure 3

The distribution of electric field norm for the fundamental mode at 1720nm.

Figure 4

simplified diagram of thulium ions.

Figure 5

Figure 6

The obtained gain of Tm:T₂O₃ versus length of the rib waveguide.

Figure 7

The distributed pump and signal powers along the waveguide.

Figure 8

The distributions of forward and backward powers along the waveguide.

Figure 9

The variation of the signal gain with the launched pump power.