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RESEARCH ARTICLE - PHYSICS

High Output Power Holmium-Doped Fiber Laser at 2100 nm

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Abstract

A theoretical model of three levels describing Holmium-doped fiber lasers pumped by Laser-diodes 1150nm is present. Based on the model, efficiency as well as output power depend on the length of active media, are investigate, using the MATLAB program (R 2019 a). The results shows that output power and efficiency of optical fibers are exponential inverse relationship with increment fiber length, for 1m output power have highest value 100.4W, while efficiency have 44.6% at 0.05m.

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Keywords: Holmium, Fiber lasers, High Output Power, laser efficiency, Fiber length.

1. Introduction

Fiber lasers are used in many scientific fields because they have many advantages for their wide applications, such as remote sensing, military treatment, and medical treatment, compared to other laser systems[1]. In these lasers, fibers made of silicate or phosphate glass absorb the raw light from laser diodes and convert it into a laser beam of a specific wavelength. To achieve this, optical fiber grafting refers to the practice of mixing a rare earth element into the fiber. By using different doping elements, lasers can be created with a wide range of wavelengths. Some common doping elements in ascending order of emitted wavelengths are neodymium (780–1100 nm), ytterbium (1000–1100 nm), praseodymium (1300 nm), erbium (1460–1640 nm), thulium (1900–2050 nm), holmium. (2022–2200 nm), and dysprosium (2600–3400 nm). Due to the wide range of wavelengths produced, fiber lasers are ideal for a variety of applications, such as laser cutting, texturing, cleaning, engraving, drilling, marking, and welding. This also enables fiber lasers to be used in many different sectors, such as medicine, defense systems, communications, automotive, spectroscopy, electricity, manufacturing, and transportation[2]. The effectiveness and power output of a 2100 nm diameter holmium-doped fiber laser are of great interest[3]. Using the fiber length as the parameter of interest, the effects of varying the output power and efficiency η which stands for the calculation of the amount of energy turned into light are explored in order to increase the laser's performance. The primary pump absorption in holmium-doped fibers is located at the 1150 nm central wavelength ($^5I_8 \rightarrow {}^5I_6$ transition).

2. Modeling

A laser system with three pumped energy levels is depicted in Fig 1. An ion at a given level in a holmium-doped fiber laser can be driven to emit at a higher or lower level, or it can spontaneously transition to any lower level (whether or not it radiates). The two fundamental transitions are depicted in the figure: the pump transition (1150 nm) and the laser transition (2100 nm).

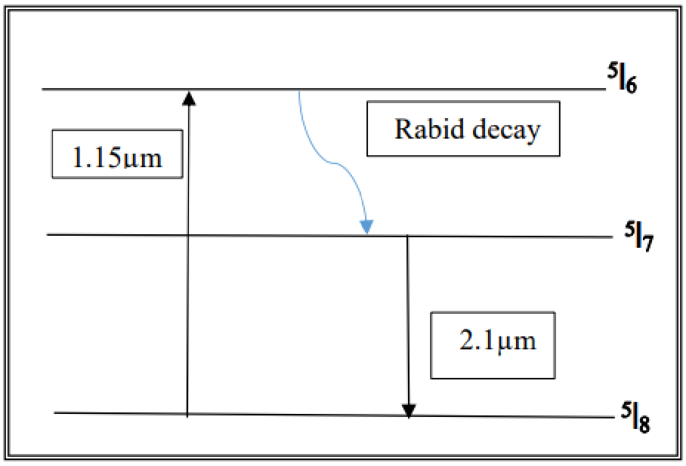

Fig. 1. energy level diagram for holmium-doped glass

The rate equations are [4]

$$\frac{dN_3}{dt} = N_1W_P - N_3X_PW_P - N_3W_3 \quad (1)$$

$$\frac{dN_2}{dt} = N_3W_{32} + N_1W_{12}^d - N_2W_2 - N_2W_{21}^d \quad (2)$$

$$\frac{dN_1}{dt} = N_3W_{31} + N_2W_{21}^d + N_2W_{21} - N_1W_{12}^d - N_1W_1 \quad (3)$$

$$N_0 = N_1 + N_{ex} \quad (4)$$

$$N_{ex} = N_2 + N_3 \quad (5)$$

Where N_i number of ions per unit volume in level *i*, W_{ij} probability per unit time that an ion in level *i* decays spontaneously to level *j* (either radiate or non-radiates). W_i total spontaneous decay rate from level *i* and W_{ij}^d is the transition rate from level *i* to level j induced by stimulated emission or absorption, N_0 is the total number of ions per unit volume, and N_{ex} is the total population in the excited states. Pump rate W_P related to the pump cross section σ_P by[5]

$$W_P = \frac{I_P\sigma_P}{h\nu_P} \quad (6)$$

Where I_P is the pump intensity & $h\nu_P$ is the pump photon energy. The term X_PW_P on the right-hand side of equation 1 corresponds to downward induced transition by the pump beam. If the level *i* have degeneracies g_i, the ratio of stimulated emission rate to absorption rate for the pump is [6] $X_P \equiv \frac{g_1}{g_4}$ the absorption and stimulated emission of the lasing radiation related by the degeneracy ratio:

$$X_r = \frac{W_{12}^d}{W_{21}^d} = \frac{g_2}{g_1} \quad (7)$$

Solving equations (1) to (5), two types of spontaneous emission branching ratio. First, $\beta_{ij} = \frac{W_{ij}}{W_i}$ is the probability that level *i* relaxes in a single step (either radiate or non-radiate) to level *j*. Second, b_{ij} is the probability that level *i* relaxes to level *j* through any combination of downward-going steps. These branching ratios defined in the absence of any stimulated emission transitions. The multistep branching ratio b_{ij} written in terms of the single-step branching ratios B_{ij} as:[7]

$$b_{ij} = \sum_{k=j}^{i-1} \beta_{ik}\, b_{kj} \quad (8)$$

where $b_{ij} = 1$.

At steady states,

$$N_1 W_P - N_3 X_P W_P - N_3 W_3 = 0 \tag{9}$$

$$N_3 W_{32} + N_1 W_{12}^d - N_2 W_2 + N_2 W_{21}^d = 0 \tag{10}$$

$$N_3 W_{31} + N_2 W_{21}^d + N_2 W_{21} - N_1 W_{12}^d - N_1 W_1 = 0 \tag{11}$$

From steady of rate equations, the output power as a function of pumping power is

$$P_{out} = P_P \frac{\tau_a \sigma_L T S I_{sat}(1-\gamma)}{2\gamma G_{th} h\nu_P (1+S)} \tag{12}$$

Where:

$\gamma = \exp\left(-\alpha_P L + a_3(1 + a_4 S) G_{th} \frac{\sigma_P}{\sigma_L}\right)$, Low intensity pump absorption coefficient (α_P) =Nσ_P, L Fiber Length, $a_3 \equiv \frac{\tau_e + \tau_P}{\tau_a}$, $a_4 = \frac{a_2 \tau_e + \tau_P}{\tau_e + \tau_P} S = W_{21}^d \tau_b = \frac{I}{I_{sat}}$, $a_2 = 1 - \frac{\tau_2 \tau_a}{\tau_b \tau_e}$,$\tau_{ex} = \tau_e \frac{1 + a_2 S}{1 + S}$, $I_{sat} \equiv \frac{h\nu_L}{\sigma_L \tau_b}$, $\tau_e = \sum_{i=2}^{4} \beta_{4i} \tau_i$,

$\tau_a = \beta_{32} \tau_2 - X_r \beta_{31} \tau_1$, $\tau_b = \tau_2 + \tau_1 X_r (1 - \beta_{21})$

And G_{th} is the gain at the threshold $G_{th} = \alpha_L L + \ln(R_1 R_2)^{-1/2}$, Fiber attenuation coefficient at the laser wavelength (α_L) =Nσ_L, $R_1 R_2$ The reflectivity of the laser mirror at the fiber and the fiber exit, respectively.

The pumping threshold P_{th} in the case of continuous wave laser is

$$P_{th} = G_{th} \frac{h\nu_p A_{eff}}{\tau_a \sigma_L} \frac{\beta}{1-\beta} \tag{13}$$

That:

$$\beta = \exp\left(-\alpha_P L + a_3 G_{th} \frac{\sigma_P}{\sigma_L}\right) \tag{14}$$

Where $h\nu_P$ is the pump photon energy, A_{eff} is the effective core area of the fiber, and σ_L is the stimulated emission cross section for the 2→1 lasing transition, σ_P Pump cross section, Low intensity pump absorption coefficient (α_P) =Nσ_P

The laser output gradient efficiency is given by the following formula [8]:

$$\eta_s = \eta_P \frac{T}{\delta} \frac{h\nu_L}{h\nu_P} \tag{15}$$

Where η_P is the percentage of the amount of pumping energy contained in the fiber core, T is the transmittance of the output mirror. The ratio of the laser photon energy to the pumping photon energy is $\frac{h\nu_L}{h\nu_P}$, this ratio constitutes the limit Essential for the efficiency, the process converting the energy of any photon into another photon, δ represents the total losses of laser intensity for the round trip.

The output power of this fiber laser given in terms of the absorbed pumping power P_{abs} by the relationship [4]

$$P_{out} = \eta_s (P_{abs} - P_{th}) \tag{16}$$

Where $P_{abs} = P_p(0)[1 - \exp(-\alpha_p L)]$ and $P_p(0)$ is the pumping power at the entrance to the doped fiber, and the laser output ramp efficiency $\eta_s$is a measure of the efficiency with which the doped fiber laser transforms the incident pumping power once it reaches Threshold limit to output power.

3. Results and discussion

Absorption power is the amount of optical pumping absorbed by the holmium-doped portion of the optical fiber per unit length. The higher the absorption power, the greater the amount of light energy that can be converted into laser light. Threshold power is the lowest amount of light energy needed to start the laser process, lower threshold power, more efficient laser. All parameters for the holmium-doped silica glass fiber laser with laser emission at a wavelength of 2100 nm and a pumping wavelength at a wavelength of 1150 nm, are shown in table1

Table 1: The basic parameters for holmium-doped silica fiber laser

Parameters	Value	unit	Reference
λ_P	1150	nm	[9]
σ_P	1.5×10^{-25}	m^2	[9]
X_P	17/13	-	Calculated
λ_L	2100	nm	[9]
σ_L	3×10^{-25}	m^2	[9]
X_r	15/17	-	Calculated
τ_2	7.35	ms	[10]
τ_3	3.521	ms	[10]
l	0.07-1.4	m	Calculated
G_{th}	0.06-0.2	-	Calculated
N_A	0.0681	-	Calculated
n_1	1.448	-	[11]
n_2	1.451	-	[11]
R_2	1	-	Assumed

Any increase in pumping power results output power linearly increase for all lengths as shown in fig.2 at the fiber core radius (r=5μm) and holmium ion concentration ($N=4\times10^{23}$ ion/m^3). Increasing fiber length L of magnitude with (0.02, 0.2 & 2) m means that **first**, decrease in efficiency η (48.7, 31.3 & 6.8) % **second**, output power P_{out} increased to (8, 50,110) W respectively, these results are in agreement with [9].

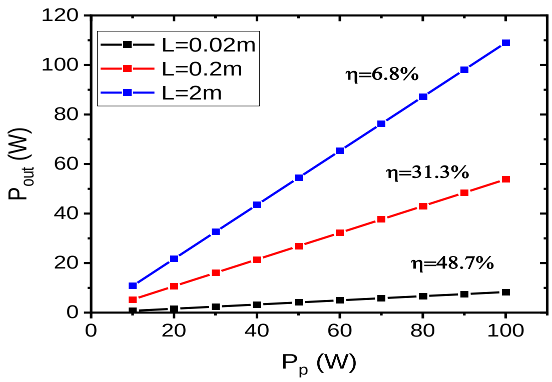

Fig. 2. Output power as a function of pump power for different lengths

at $N=4\times10^{23}$ ion/m^3, r=5μm.

At pumping power 100W, fig.3 shows output power & efficiency as a function of fiber length. For different length from (0 to 1) m output power increased exponentially from 19.2W at 0.05m to 100.4W at 1m, while efficiency decreased exponentially from 44.6% to 12% as shown in fig.3a, these results are coincided with [12]. At the same pumping power 100W, fig.3b explain there is no alternating in output power (Pout ≈100W), notice an approximate stability in the output power whenever the length of the fiber increased from 1-2m. Increasing energy leads excess in glowing cause's low efficiency and decrease in stability of the laser, high distortions with damage fiber due to rising fiber temperature.

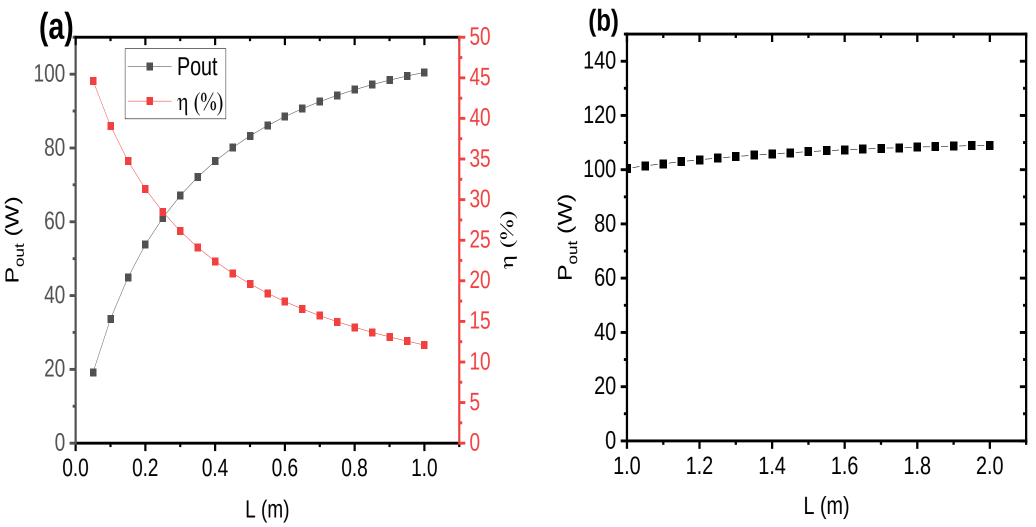

Fig. 3. a- output power and laser efficiency are a function of fiber length at P_p =100 W, b- output power is a function of the fiber length at P_p =100W, N=4×10^{23} ion/m^3 & r=5 μm.

The discrepancy between efficiency and output power results in transmission loss due to the parameters absorption power P_{abs} and threshold power P_{th} High P_{abs} with increasing fiber length, as shown in Fig. 4. Rise optical length l leads to large amount of light absorbed by the holmium ions, so loss of energy.

P_{th} is important determiner for energy, needed to start the laser process, at low value of P_{th} sense laser process has started. Threshold limit G_{th} boost with growing length of holmium-doped fiber laser, Table1, due to execs optical scattering. Light scattering is the process of light being deflect from its path purpose differences in the properties of the medium through which the light passes. In holmium-doped fibers laser, occurs of light scattering mean non-uniformity in fiber ions distribution results energy loss, requires more energy to initiate the laser process in a longer fiber. Therefore, high threshold with large fiber length. Fig. 4 shows that longer fibers give greater absorption power, and greater threshold power.

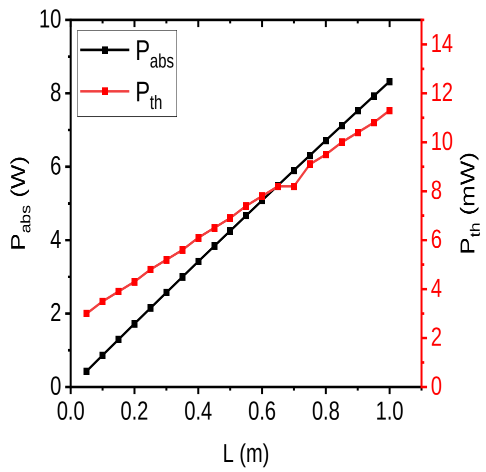

Fig. 4. absorption power and threshold power as a function of fiber length at N=4×10^{23} ion/m^3, r=5μm.

4. Conclusions

Light scattering grows with fiber length, which is the main reason for the inverse relationship between fiber length and efficiency. Light scattering occurs due to the irregular distribution of holmium within the fiber, so the laser beam loses energy and reduces efficiency. There are other factors, besides light scattering, that can affect the inverse relationship between fiber length and efficiency. For example, lengthening fibers can result in more radiation that is not absorbed, which also reduces energy. We thus conclude that the best fiber length used is 1 m, which achieved the highest production power of 100.4 W. The threshold limit increases with the length of the holmium-doped fiber laser.

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