International Journal of Optoelectronic Engineering 2021, 10(1): 1-8
DOI: 10.5923/j.ijoe.20211001.01

Design of Yb^{3+} Doped Laser for Industrial Application

Moses Simpungwe*, Charles Lubobya, Sampa Nkonde

Department of Electrical and Electronic Engineering, University of Zambia, Lusaka, Zambia

Abstract This paper presents a model design of Yb^{3+} doped fiber laser (YDFL), for industrial applications. The system‘s 980 nm pump lasers are set to 34 W in bidirectional pumping and in Continuous Mode (CW) scheme. The basic idea of modelling the laser device was to ensure that the parameters: pump power, active fibre cable and Yb^{3+} ion concentration are optimised for better quality laser output power. Further, output coupling (OC) and highly reflective (HR) mirrors are incorporated in the Dichroic couplers for best combination of signals. The calculations provide a coherent insight into optimized Yb^{3+} length and concentrations. Simulations using MATLAB were conducted. Results show that Output power of 58.64W, at lasing wavelength of 1018nm was achieved when pump power of 68W was launched in the cavity, giving a slope efficiency of 87.71%. The operational characteristics of this Yb^{3+} doped fibre laser promises significant applications in radar, laser machining, free space communication and medical treatment.

Keywords Ytterbium doped fibre laser (YDFL), Output coupling (OC), Highly reflective (HR), Dichroic coupler, Optimised, Pumping, Simulations

1. Introduction

Since 1961, when the first fiber waveguide was proposed [1], the progress of fiber lasers in terms of application and output powers has seen a huge successful technological development. In the rare earth elements (RE), Neodymium was the first element to be doped with silica in 1964 to produce the neodymium doped fiber laser [2], followed by Erbium doped fiber laser in 1987 [3]. In 1988, Ytterbium doped fiber laser was proposed and demonstrated [4]. Over the years, fiber lasers (FLs) have become increasing known in the field of scientific and commercial application, largely as a result of the outstanding characteristics they portray [5-7]. Fiber lasers are best known for their high average power and beam qualities compared to other types of lasers. The critical part of fiber laser module is the rare earth (RE) doped active fiber cable. Ytterbium has simple energy level diagram which portrays merely a ground state, $^2F_{7/2}$, and meta-stable state, $^2F_{5/2}$ separated by nearly 10,000 cm^{-1}. This huge gap between the two states reduces some of the drawbacks, such as excited state absorption phenomenon (ESA), associated with other rare earth doped-fibers. The presence of ESA in the Ytterbium doped fibers reduces the pump efficiency and concentration quenching through transfer of energy between the interior sub levels [8]. Ytterbium-doped fiber Lasers (YDFLs) have been shown to be an ideal choice for lasing and amplifying in the 1000 – 1200nm spectral region [9-11]. There are a lot of theoretical and experimental models [12-22] of the YDFL, pumped around 976nm, lasing at 1018nm, deploying Fiber Bragg Gratting (FBG), based on rate equations and power equations. None the less, to our knowledge, there are no studies that discuss the theoretical modeling of Yb^{3+} doped fiber laser pumping at 980nm wavelength with 68W power in bidirectional pumping scheme and lasing at 1018nm wavelength. In this paper, a theoretical Yb^{3+} doped fiber Laser device for industrial application is presented. In this model, pump wavelength and lasing wavelength of 980nm and 1018nm respectively are used. The model deployed Dichroic couplers on the input and output of the linear cavity. The effect of variation, in the pump power, the active fiber length and the active ion (Yb^{3+}) concentrations on the output laser power are extensively explored.

* Corresponding author:
simpungwem@yahoo.com (Moses Simpungwe)
Received: Dec. 10, 2020; Accepted: Dec. 26, 2020; Published: Jan. 15, 2021
Published online at http://journal.sapub.org/ijoe

2. Yb^{3+} Doped Laser

Yb^{3+} doped laser is an active fiber cable doped with ytterbium element. Ytterbium is a rare earth material used in doping silica glass to improve the characteristics of the active fiber cable such as low noise and gain in the output power. Unlike other rare earth elements such as erbium, thulium, neodymium etc which are equally used as dopants in fiber lasers, Ytterbium ion does not have higher energy levels which significantly minimize the occurrence of multi-photon relaxation as well as excited state absorption (ESA). Ytterbium ions also have emission as well as absorption cross sections that are usually many times greater compared to other rare-earth ions in multi-component glasses. Coiling the gain fiber of an amplifier is one method utilized to effectively depress high-order modes [23]. The flexibility of ytterbium ion in doped silica fibers is one of its strong points. Ytterbium ions exhibit strong scientific properties, particularly in its broad absorption band that ranges from slightly below 850 nm to more than 1070nm [24].

3. Theoretical Model

The conceptual model for the designed device involving Yb^{3+} doped fiber with 60 W output power is as outlined in Figure 1 below.

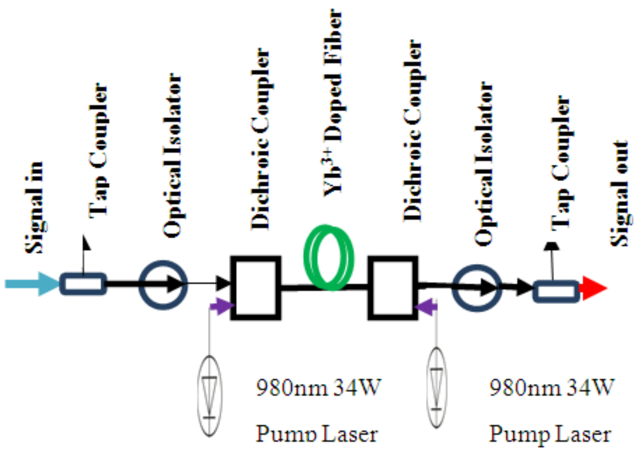

Figure 1. Schematic model of 1018nm Doped laser

The formulation of rate equations in this paper is on the analysis based on the quasi-3 level system. The Yb^{3+} ions electronic structure is shown in figure 2 below, with only the two main energy levels critical in the light amplification process, the lower manifold $^2F_{7/2}$ and the upper manifold $^2F_{5/2.}$

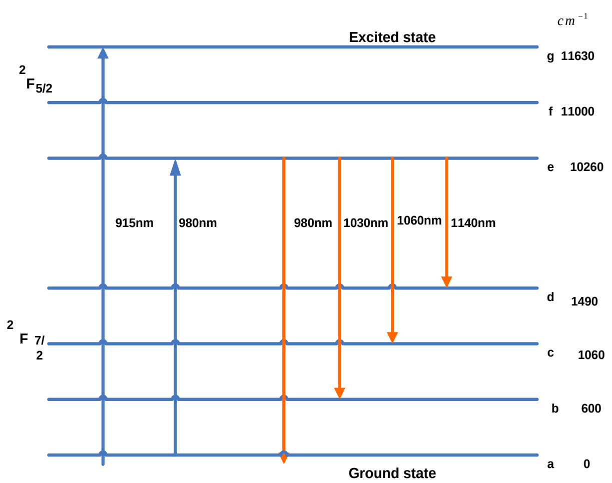

Figure 2. The Yb^{3+} energy level structure, consisting of lower manifold and upper $^2F_{7/2}$ manifold with their $^2F_{5/2}$ respective stark levels

The transition time between upper manifold and lower manifold for Yb^{3+} ions doped in silica host is approximately 880us. Ytterbium exhibits a quasi three level system at wavelengths pumping below 990nm and lasing wavelengths of around 1020nm to 1050nm.In this study, pumping wavelength of 980nm, signal wavelength of 1018nm and pump power of 34watts in bidirectional pumping was considered. Figure 2 was analyzed to support the choice of the chosen wavelengths. With pump wavelength of 980nm, the transitions from upper manifold stark level e, the transitions can come to a or b of the lower manifold in the range of 980nm to 1030nm. Within this range of wavelength lasing, ytterbium exhibits quasi-three level system. The transitions can also be noticed from stark level e, to stark levels c or d of the lower manifold. These transitions in the lasing wavelength range of 1060nm to 1140nm exhibits quasi-four level system in the ytterbium ions. The transitions between the stark levels in each manifold are even shorter than the transitions between the upper and lower manifolds such that the Yb^{3+} ions in the fiber are effectively in either upper or lower manifold. With this transition analysis, the gain medium may be modeled as a two level system whose rate equations and propagation equations are given as follows [8].

$$\frac{dN_2}{dt} = (R_{12} + W_{12})N_1 - (R_{21} + W_{21} + A_{21})N_2 \tag{1}$$

Where:

N_1 and N_2 are the normalized populations in the lower and upper energy levels, R_{12} and R_{21} are the pump excitation and de-excitation rates respectively.

W_{12} and W_{21} are the signal absorption and emission respectively and A_{21} denotes the spontaneous emission rate.

The pump and signal transition rates in a fiber waveguide are determined from the absorption emission cross section of the ions in the host medium. These are written as:

$$R_{12} = \frac{\sigma_{R12} I_p}{h\nu_p}, \quad R_{21} = \frac{\sigma_{R21} I_p}{h\nu_p} \tag{2}$$

$$W_{12} = \frac{\sigma_{W12} I_s}{h\nu_s}, \quad W_{21} = \frac{\sigma_{W21} I_s}{h\nu_s} \tag{3}$$

Where:

I_p and I_s are the pump and signal power intensities respectively, ν_p and ν_s are the pump and signal transition frequencies respectively, h is the Planck's constant, σ_{R12} and σ_{R21} are pump absorption and emission cross sections respectively, σ_{W12} and σ_{W21} are signal absorption and emission cross sections respectively and the spontaneous emission rate is given by:

$$A_{21} = \frac{1}{\tau} \tag{4}$$

Where τ is the life time of Yb^{3+} ions in the excited state.

Considering the lower and upper energy levels and applying the law of energy conservation, equation in (4) is obtained. This equation is referred to as ion density equation that is given by [8].

$$N_1 + N_2 = N_t \quad (5)$$

Under steady state conditions:

$$\frac{dN_1}{dt} = 0, \ \frac{dN_2}{dt} = 0 \quad (6)$$

And therefore,

$$N_2 = \frac{R_{12} + W_{12}}{R_{12} + W_{12} + R_{21} + W_{21} + A_{21}} \quad (7)$$

Considering the rate equations from the energy level diagram and assuming no pump and signal scattering losses, the pump power propagation at 980nm wavelength along the fiber is given by:

$$\frac{dP_{(980)}(z)}{dz} = \{(-\sigma_{R12}N_1 + \sigma_{R21}N_2)N_t\Gamma_{p(\lambda=980)}\}P_{(980)}(z) \quad (8)$$

And Signal power variation at 1018nm wavelength along the fiber is given by the propagation equation:

$$\frac{dP_{(1018)}(z)}{dz} = \{(-\sigma_{W12}N_1 + \sigma_{W21}N_2)N_t\Gamma_{s(\lambda=1018)}\}P_{(1018)}(z) \quad (9)$$

Where,

z denotes the active fiber length, $\Gamma_{p(\lambda=980)}$ is the pump overlap factor defined as a ratio of pump core area over doped area and $\Gamma_{s(\lambda=1018)}$ is the signal overlap factor defined as the overlap of mode field area with doped area.

From (14), the signal propagation equation, we get the small signal gain coefficient g(z) written as:

$$g(z) = (-\sigma_{W12}N_1 + \sigma_{W21}N_2)N_t\Gamma_{s(\lambda=1018)} \quad (10)$$

For Bidirectional propagating scheme, the gain, G, is obtained by integrating the gain coefficient in (10), over the length of the active fiber as:

$$G = N_t\Gamma_s \int_0^L (-\sigma_{W12}N_1 + \sigma_{W21}N_2)dz \quad (11)$$

And also consider the boundary conditions for forward (P_S^+) and backward (P_S^-) propagating laser, respectively are given by [19]:

$$P_S^+(0) = R_1 P_s^-(0) \quad (12)$$

$$P_s^-(L) = R_2 P_S^+(L) \quad (13)$$

Where:

R1 and R2 are the power reflectiveness of the mirrors in the resonator cavity positioned at a distance of L apart and

$$P_s^-(z)P_S^+(z) = \text{constant} \quad (14)$$

The stationary condition for a linear cavity fiber laser given as shown below;

$$R_1 R_2 \exp(2G) = 1 \quad (15)$$

For lasing to take place, the population in the N_2 must be more than the population in N_1 and this is achievable by ensuring enough gain and appropriate threshold power. Substituting equation (8) and equation (9) in equation (11) and applying the stationary condition given in (15), yields the gain and laser output power given as [25]:

$$G_p = \ln[P_p(L)/P_p(0)]$$

$$G_p = \frac{\Gamma_p \sigma_p}{2\Gamma_s \sigma_s}\ln\left(\frac{1}{R_1 R_2}\right) - \frac{\sigma_{w21}\sigma_{R12} - \sigma_{R21}\sigma_{W12}}{\sigma_S}\Gamma_p N_t L \quad (16)$$

From (16), the laser output power is obtained as:

$$P_{out} = (1 - R_2)P_s^+(L)$$

$$P_{out} = \frac{\lambda_p}{\lambda_s}\frac{(1-R_2)P_p^{sat}}{1 - R_1 - \sqrt{R_1 R_2} + \sqrt{R_1/R}_2} X\left[\frac{P_p^+(0) + P_p^-(L)}{P_p^{sat}} - (1 - \exp(G_P) - G_p - \Gamma_p N_t \sigma_{R12} L\right] \quad (17)$$

Where: P_p^{sat} is the pump saturation power (the power that reduces the absorption coefficient by a factor of 2 given as follows [25]:

$$P_p^{sat} = \frac{h\nu_p A}{\sigma_p \Gamma_p \tau} \quad (18)$$

And P_s^{sat}, is the signal saturation power given by:

$$P_s^{sat} = \frac{h\nu_s A}{\sigma_s \Gamma_s \tau} \quad (19)$$

Where: *A*, is the effective core area.

4. Implementation Methodology

In modeling the Yb^{3+} doped Laser, a quantitative approach was used. Linear differential equations were solved in determining the variations in pump power, active fiber cable length and YB^{3+} ion concentrations. Simulations were done using Computer software simulation-Matlab based on the simplified two –level rate equations and propagation equations formulated from the energy level diagram.

In Figure 1, bidirectional pumping configuration was used in the oscillator deploying wavelength stabilized laser diodes, double clad YDF, dichroic coupler with high reflection (HR) and output coupling (OC). The total pump power (68W) of two laser diodes with centre emission at 980nm was launched into the dichroic coupler, and then was absorbed in the active fiber. The HR and OC have reflectivities of 100% and 30% at a center wavelength of 1018nm respectively. The active fiber is Yb^{3+} doped with core diameter of 30um with NA of 0.08, cladding diameter of 250um (NA 0.46). The YB^{3+} ion concentration was 1e27m-3 and life time of the ions in the upper level of 0.8ms. The theoretical model regards the pump (980nm) as a monochromatic signal. Its length was optimised by simulations independent of the maximum achievable output power.

5. Results and Discussions

This research critically looked at the Laser output power behavior of the laser by considering three parameters. These are: laser output power vs. input pump power, laser output power vs. active fiber cable length and laser output power vs. input power at different ytterbium ion concentration levels. The research also looked at the laser output power at different input pump powers. The results are now discussed:

Figure 3, considers the relationship between input pump power and laser output power. The results show that the laser output power increased as the input pump power increased. This result is similar to the one obtained in [20] except theirs considered pump power in the range 0 to 56W.

In Figure 4, we considered the relationship between the laser output power and the active fiber cable length. A maximum laser output power of 58.64W was achieved at cable length of 0.5m, when 68W of pump power was launched, giving an optical efficiency of 87.71%. The results in figure 4 are similar to the results obtained in [21] except theirs considered active cable length of 7m. The results also show that the power output was highest at 0.5m active cable length representing 87.71% efficiency. Slightly above 0.5m, it started dropping gradually up to 24.73W at 5m active cable length representing 36.36%. This model shows that fiber laser operate well at shorter active cable length. Longer active cables are prone to introduction of noise leading to poor lasing in the cable due to re-absorption. This means that the model has a good design of using a shorter cable length. This is very good in that it reduces the cost of the device. Further, this model will not encounter re-absorption in the laser device. It further means that the noise levels in the device will be negligible as per the assumption made of negligible ASE and ESA from the design perspective. The model shows that the device will work well up to 2.5m of active fiber cable. Figure 5 shows the relationship between the laser output power and the Yb^{3+} ion concentration (Nt).

Figure 5 shows that variation in Yb^{3+} ion concentration has an effect on the output power. From figure 5, it can be seen that an output power of 29.69W was achieved at Nt of 1e26. When Nt was put at 1e27, the output that was obtained increased to 59.64W. At Nt of 1e28, the power output reduced to 24.73W. The results in figure 5 is similar to results obtained in [22] except theirs only considered output power at one ion density and pump power in the range of 0 to 1200W. This clearly shows that there is need to optimize the Yb^{3+} ion concentration in the design of the Yb^{3+} doped fiber lasers. Highly doped lasers perform well in shorter active cables. Bidirectional pumping scheme used in this model helps to ensure quick absorption takes place in the active laser fiber thereby reducing on the noise in the laser device.

Figure 6 shows the results obtained in varying of pump power at three different levels. The results show that the output power increases with increase in pump power. This result is similar to the results obtained in [22] except theirs was pumped in the range from 0 to 1200W.

Figure 7 shows the laser output power with respect to the pump power of 1114wattts launched into the active fiber cable. From figure 7, it can be seen that Laser output power of 902.86watts at pumping power of 1114watts was achieved through the simulation at the active cable length of 1.5m. The result is similar to the one obtained in [22] except theirs was pumped at 976nm wavelength and ours was pumped at 980nm wavelength.

The slope efficiency of output power to the launched pump power was achieved at 81.05% at pumping wavelength of 980nm. In a reference model with pumping wavelength of 976nm, Laser output of 875.28watts was obtained at 1.5m as shown in figure 7. The slope efficiency of 78.57 was achieved. The simulation at pump wavelength of 980nm shows better result than pumping at 976nm.In the same comparison study, figure 8 shows the laser output power in relation to the active fiber cable length.

In Figures 7 and 8, the output coupling mirror was at 14.9% and the highly reflective mirror was at 99.5%. From figure 8, at pump wavelength of 980nm, the laser output power at 1m length was 881.41watts. At 1.5m it increased to 902.87watts and gradually started falling at 2m until it reached 807.43watts at 5m. The indication is that the optimum power was reached at 1.5m with slope efficiency of 81.05%. This means that using a longer active fiber cable is not profitable. In any case a shorter cable is ideal in that the cost is cheap and the device would be small in size. The results in figure 8 are similar to results obtained in [21] except theirs considered active fiber cable length of 7m producing highest laser output power at 4.5m length.

Table 1, shows the effect on the output power of keeping the active fiber length and ion concentration constant while varying the pump power. From Table 1, it can be concluded that the variation on the pump power gave an efficiency of 87.71%. This shows that the model is very efficient.

Table 1. Pump power vs. laser output power

Pump power (W)	output power (W)	Efficiency (%)
48	42.10	87.71
68	59.64	87.71
88	77.18	87.71

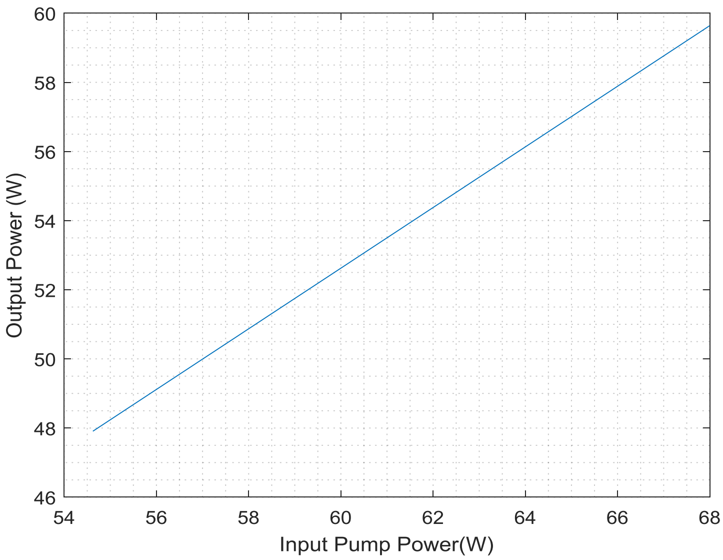

Figure 3. Input pump power vs. output power

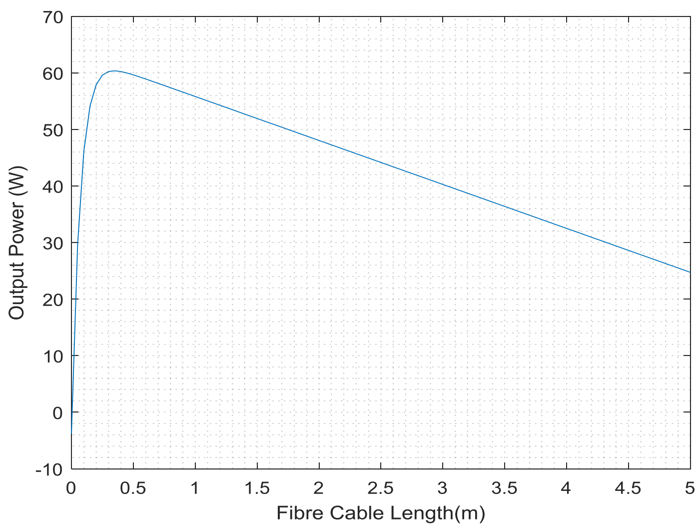

Figure 4. Active fiber cable length vs. Output power

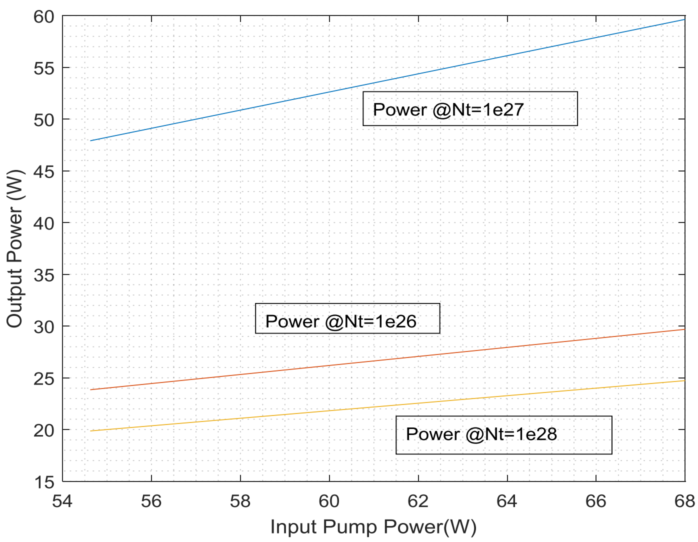

Figure 5. Modeling results Laser output at Nt of 1e26, Nt of 1e27, and Nt of 1e28 deploying HR of 100% and OC of 30%

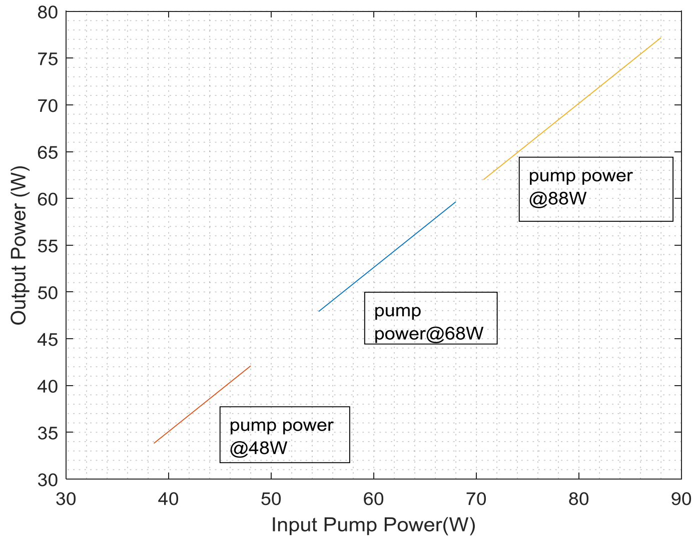

Figure 6. Modeling results -Laser output at pump power of 48W, 68W, and 88W

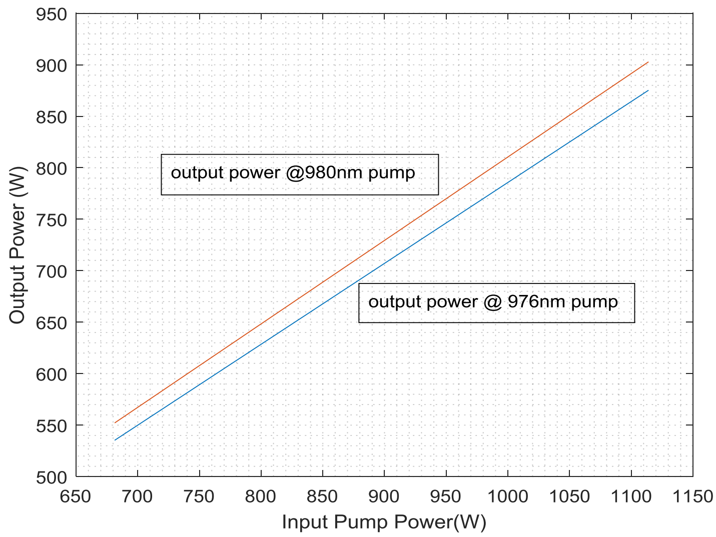

Figure 7. Modeling results of Laser output power vs. Input pump power

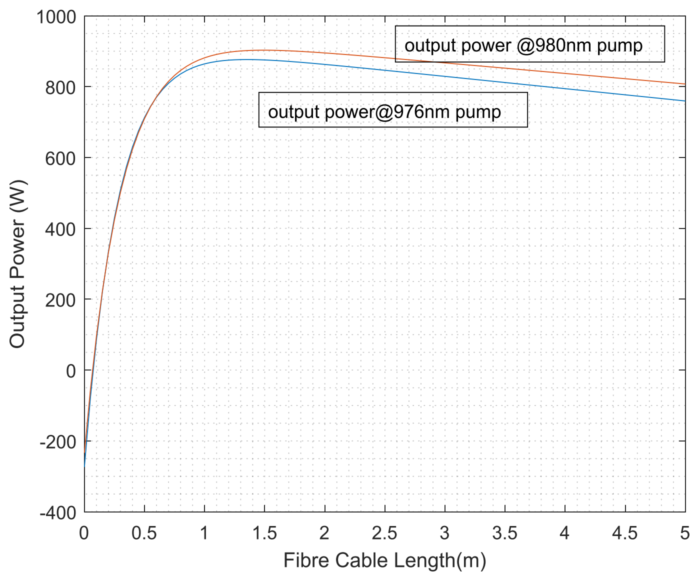

Figure 8. Modeling results of Laser output power vs. active fiber cable length

6. Conclusions

The study modeled a 1018nm fiber laser pumping at 980nm.It is found that reducing the active fiber cable length and increasing the Yb^{3+} ion concentration produces high laser output power. Further, the study revealed that the dichroic coupler of HR of 100% and OC of 30% is ideal for a YDFL. Slope efficiency of 87.71% was achieved which indicates good record as most studies showed achievement of slope efficiency below 80%. The study shows that optimizing the parameters i.e. pump power, active fiber length and YB^{3+} ion concentration is critical in modeling/ designing the fiber lasers. Future works should include conducting an experimental design to this theoretical model and comparing it to our results. Furthermore, researchers should also consider using the combination of FBG and dichroic couplers.

ACKNOWLEDGEMENTS

We wish to recognize and acknowledge the contribution made by individuals/friends towards this study. We also value the funding towards this work from the research team.

REFERENCES

[1] E. Snitzer, "Proposed fiber cavities for optical lasers," Journal of Applied Physics, vol. 32, no. 1, pp. 36–39, (1961).

[2] E. Snitzer, "Neodymium glass laser," in Quantum Electronics, vol. 1, p. 999, (1964).

[3] R. J. Mears, L. Reekie, I. M. Jauncey, and D. N. Payne, "Low-noise Erbium doped fiber amplifier at 1.54 _m," Electronics Letters, vol. 23, no. 19, pp. 1026–1028, (1987).

[4] D. C. Hanna, R. M. Percival, I. R. Perry, R. G. Smart, P. J. Suni, J. E. Townsend, and A. C. Tropper, "Continuous-wave oscillation of a mono mode Ytterbium-doped fiber laser," Electronics Letters, vol. 24, no. 17, pp. 1111–1113, (1988).

[5] C. Jauregui, J. Limpert, and A. Tünnermann, Nat. Photonics 7, 861 (2013).

[6] V. R. Supradeepa and J. W. Nicholson, Opt. Lett. 38, 2538 (2013).

[7] W. Shi, Q. Fang, X. Zhu, R. A. Norwood, and N. Peyghambarian, Appl. Opt. 53, 6554 (2014).

[8] Fady I, El-Nahal, Abdel Hakeim M, Hsein," Temperature Dependency of Ytterbium-Doped Fiber Laser (YDFL) Based on Fabry-Perot Design Operating at 915 nm and 970nm High Power Pumping Configuration" JERT volume. 3, no.1, pp.1748, (2016).

[9] Pask HM, Carman RJ, Hanna DC et' al."Ytterbium-doped silica fiber lasers: versatile sources for the 1–1.2 μm region," IEEE J. Sel. Top. Quantum. Electron. 1, 2-12, (1995).

[10] Paschotta R, J. Nilsson, A. C. Tropper, and D. C. Hanna, "Ytterbium-doped fiber amplifiers," IEEE J. Quantum. Electron. 33, 1049-1056, (1997).

[11] Nilsson J, Sahu J.K, Jeong Y, Clarkson A, et 'al, "High power fiber lasers," Proc. SPIE 4974, 50-59. (2003).

[12] Zhen Li, Jun Zhou, Bing He, Xijia Gu, Yunrong Wei, Jingxing Dong, and Qihong Lou," Diode-pumped 1 018-nm ytterbium- doped double-clad fiber laser", Chinese Optics Letters, Vol.9, no.9, pp 091401, (2011).

[13] T. Sakimura et al., "1.5-μm high-gain and high-power laser amplifier using a Er, Yb: glass planar waveguide for coherent Doppler lidar," in Proc. CLEO, San Jose, p. 114, (2012).

[14] Xiao, H., Zhou, P., Wang, X., Guo, S., & Xu, X. "Experimental Investigation on 1018-nm High-Power Ytterbium-Doped Fiber Amplifier", IEEE Photonics Technology Letters, vol.24, no.13, pp.1088–1090, (2012).

[15] Xiao, H., Zhou, P., Wang, X. L., Xu, X. J., & Liu, Z. J., "High power 1018 nm ytterbium doped fiber laser with an output power of 309 W", Laser Physics Letters, vol.10, no.6, (2013).

[16] Sen, R., Saha. M., Pal.A., Pal. M., Leich. M., Kobelke. J.," High power laser fiber fabricated through vapor phase doping of Ytterbium", Laser Physics Letters, vol.11, no.8, p.085105, (2014).

[17] Wang, Y., Ke, W., Sun, Y., Ma, Y., Li, T., Feng, Y., & Wu, J." Research of high brightness 1018nm ytterbium doped fiber laser", XX International Symposium on High fiber laser", Power Laser Systems and Applications, (2015).

[18] C. Ottenhues, T. Theeg, K. Hausmann, M. Wysmolek, H. Sayinc, J. Neumann, and D. Kracht, "Single-mode monolithic fiber laser with 200 W output power at a wavelength of 1018 nm," Opt. Letters, Vol.40, pp.4851–4854, (2015).

[19] Yang, H., Zhao, W., Si, J., Zhao, B., & Zhu, Y., "126 W fiber laser at 1018 nm and its application in tandem pumped fiber amplifier", Journal of Optics, vol.18, no.12, pp.125801, (2016).

[20] Glick, Y., Sintov, Y., Zuitlin, R., Pearl, S., Shamir, Y., Feldman, R., Shafir, N. "Single-mode 230 W output power 1018 nm fiber laser and ASE competition suppression", Journal of the Optical Society of America B, vol.33, no.7, p.1392, (2016).

[21] Y. Midilli, O. B. Efunbajo, B. şimşek, and B. Ortaç, "1018 nm Yb-doped high-power fiber laser pumped by broadband pump sources around 915 nm with output power above 100 W," Appl. Opt., vol. 56, no. 25, p. 7225, (2017).

[22] Ping Yan et'al.," High-power 1018 nm ytterbium-doped fiber laser with output of 805W", Optics Letters, Vol. 42, No. 7, p.1193, (2017).

[23] L. Huang, W. Wang, J. Leng, S. Guo, X. Xu, and X. Cheng, "Experimental investigation on evolution of the beam quality in a 2 kW high power fiber amplifier," IEEE Photon. Technol. Lett.vol. 26, pp.33–36, (2014).

[24] H. Xiao, J. Leng, H. Zhang, L. Huang, J. Xu, and P. Zhou, "High-power 1018nm ytterbium-doped fiber laser and its application in tandem pump," Appl. Opt., vol. 54, pp. 8166-8169, (Sep 2015).

[25] Xiao, L., Yan, P., Gong, M., Wei, W., & Ou, P. "An approximate analytic solution of strongly pumped Yb-doped double-clad fiber lasers without neglecting the scattering

loss", Optics Communications, vol. 230, no. (4-6), pp.401–410, (2004).