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1018 nm Yb-doped high power fiber laser pumped by broadband pump sources around 915 nm with output power above 100 W

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We demonstrate a 1018 nm ytterbium-doped all-fiber laser pumped by tunable pump sources operating the broad absorption spectrum around 915 nm. In the experiment, two different pump diodes were tested to pump over a wide spectrum ranging from 904 nm to 924 nm by altering the cooling temperature of pump diodes. Across this so called pump wavelength regime having 20 nm wavelength span, the amplified stimulated emission (ASE) suppression of the resulting laser was generally around 35 dB showing good suppression ratio. Comparisons to the conventional 976 nm pumped 1018 nm ytterbium-doped fiber laser were also addressed in this study. Finally, we have tested this system for high power experiment and obtained 67% maximum optical to optical efficiency at approximately 110 W output power level. To the best of our knowledge, this is the first 1018 nm ytterbium-doped all-fiber laser pumped by tunable pump sources around 915 nm, reported in detail.

OCIS codes: (140.3490) Lasers; (060.2420) Fibers; (060.3735) Fiber Bragg gratings; (140.3510) Lasers, fiber; (140.3615) Lasers, ytterbium

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1. INTRODUCTION

Ytterbium-doped fiber lasers (YDFL) operating at 1018 nm wavelength have a lot of applications especially as pump sources in tandem configuration for high power amplifiers [1–4], pulsed lasers [5], and random fiber lasers [6]. In the case of tandem pumping, 1018 nm YDFLs are very efficient pump sources for high power lasers with outputs at higher wavelengths, such as 1060 nm - 1080 nm, due to lower quantum defect and higher brightness compared to the conventional 915 nm or 976 nm diode pump sources [7], i.e. an upper limit to the output power or optical-to-optical efficiency [8]. The quantum defect is about 8% - 10% when a 1060 nm - 1080 nm YDFL is pumped by a 976 nm pump source, compared to 4% - 6% when the YDFL is pumped by a 1018 nm fiber laser. This low quantum defect by using a 1018 nm pump source allows for potentially higher power efficiency, and indeed fiber laser amplifiers pumped by 1018 nm YDFLs with good efficiencies have been reported [1, 2, 4]. Additionally; core-pumped, single mode, high power 1018 nm YDFLs usable for high power pump sources have also been demonstrated [9, 10]. Yb-doped fibers have two prominent absorption regions; the narrow region but relatively high absorption cross section around 976 nm and the broad region but lower absorption cross section around 915 nm. Since the absorption cross section around 976 nm is higher than the one around 915 nm, almost all 1018 nm YDFLs employ the use of pump sources around the 976 nm region. However, one of the main challenges with using 976 nm sources is ensuring the wavelength stability of pump sources during laser operation. This is due to the narrowness of the absorption spectrum of ytterbium ions around 976 nm wavelength region. For the stabilization of the operation of the pump diodes during laser operation there are some important parameters such as operating temperature and electrical requirement which affect the output central wavelength of the pump diodes. Therefore; a careful thermal management is required for the stabilization of the pump diodes. Even with optimal cooling, the output spectrum of the pump diodes may broaden at high power application as a result of increased driving current. Since the absorption spectrum around 976 nm has narrow bandwidth, to maintain the operation of the pump diode at 976 nm is also a challenging issue. This situation can be overcome by the use of wavelength-stabilized diode lasers. Wavelength stabilization can be achieved by several approaches including the use of volume Bragg gratings (VBG) [11, 12]. VBG stabilization reduces the sensitivity of the laser diodes to temperature variance and increasing driving current. In the literature [11], VBG wavelength stabilization was also shown to narrow the bandwidth of the laser diode from 10 nm to 1 nm. In spite of all these advantages, the use of VBG stabilization has its own drawbacks. Firstly, it is not a cost effective approach and due to the pump laser diode being an aggregated stacks of smaller diodes coupled together, non-uniform cooling these individual diodes stacks can broaden the output spectrum and also make wavelength stabilization challenging [11]. On the other hand; although it has lower absorption cross section compared to 976 nm wavelength regime, the spectral region around 915 nm, another important absorption regime for Yb-doped fibers, offers a broad range of wavelengths usable for pumping 1018 nm YDFLs.

In this study, based on the information given above we have motivated that this pumping wavelength range (915 nm) coupled with well optimized parameters -such as active Yb ion doping concentration, the length of the active fiber, and output coupler reflectivity- can offer a robust tunable pumping scheme for 1018 nm YDFLs. One of the main challenges of producing YDFLs operating at 1018 nm is the gain competition at around 1030 nm due to the much higher emission cross-section in this wavelength range compared to 1018 nm. To reduce the ASE or parasitic lasing, a low Yb ion-doped active fiber, with high core-cladding ratio and an optimized length should be implemented [7, 13]. Angle-cleaving the end of the output fiber prevents back reflection from Fresnel reflection allowing for a more efficient oscillation and consequently lasing at 1018 nm. In this paper, we have demonstrated that the broad absorption spectrum around 915 nm provides viable and tunable pumping wavelengths with good efficiency and ASE suppression. The generated laser spectrum also showed stable operation as well as very minimal efficiency drops as pumping wavelengths are varied from 904 nm to 924 nm. That means even the temperature changes dramatically due to the fact mentioned above the laser operation will not be affected. Additionally, we have demonstrated an output power above 100 W achieved by 915 nm pump diodes for the first time.

2. EXPERIMENTAL SETUP

The schematic representation of the experimental setup is shown in **Fig.1**; consisting of a single pump diode source coupled into the active fiber through high reflectivity fiber Bragg grating.

The active fiber is an Yb-doped large mode area fiber (LIEKKI Yb700-30/250) having 30 μm core, 250 μm cladding with absorption coefficient of 2.2 dB/m around 920 nm. The high reflectivity (HR) and output coupler (OC) fiber Bragg gratings (FBG) had reflectivity of 99.5% and 26% respectively. Both FBGs were germanium doped (GD) LMA (with the same dimensions as the active fiber) with central wavelength at 1018 nm. As will be realized from **Fig.1**; no pump combiner was employed in the cavity design for the sake of compactness. However; this type of configuration without a pump combiner might be dangerous for the laser diode at high pump power level since 0.5% of the laser power pass through the HR-FBG and come across the laser diode. Although laser diodes have protection window upon the laser signal between 1030 nm and 1060 nm, the protection is not that much strong for 1018 nm wavelength. For that reason, the laser diode was operated by not exceeding the pump power above 30 W. Two different pump diodes were used in order to cover the 904 nm – 924 nm pumping spectrum. The first diode, "Diode 1" operates from 904 nm through 914 nm, while, the second diode, "Diode 2" operates from 914 nm to 924 nm. Operational central wavelengths of laser diodes are usually changed with respect to the input driving current. However, in this work instead of changing the driving current we are going to tune the operational wavelengths of laser diodes by alternating their operating temperatures by keeping the driving current fixed with the help of a temperature control unit. By this way, we were able to maintain the pump power at a moderate level and just change the operational wavelength of the pump diodes by controlling their operational temperature. Therefore; we were able to investigate the laser operation and the change in its efficiency.

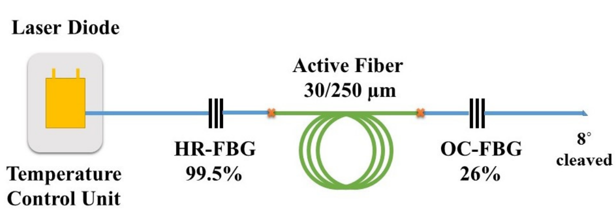

Fig. 1. Schematic of the experimental setup of the 1018 nm YDFL pumped by tunable pump sources around 915 nm including HR-FBG, OC-FBG, active fiber and the angle-cleaved output end.

3. NUMERICAL ANALYSIS

In order to achieve the intended maximum power for our laser system with minimal undesired effects -such as ASE and residual pump, the performance of the system was first investigated on a numerical simulation. Optimal OC-FBG and active fiber lengths were taken into consideration. Several experimental works [1–3, 13] on 1018 nm YDFLs pumped 976 nm with high efficiency report that the optimal OC-FBG reflectivity could be around 10% - 30%. Maximal output power and the laser efficiency was also studied by varying OC-FBG reflectivity values from 10% to 30% in our configuration (see **Fig.2a**). Our simulation results show that the optimal OC-FBG could be around 30% compared to 10%. According to the simulation results and manufacturing possibilities, an OC-FBG of 26% was chosen. The laser output power against varied active fiber length was also studied (**Fig.2a**) with respect to different OC-FBG values. Although the numerical simulations showed that an active fiber length of 5 m would be optimal, however upon experimental analysis, the optimal length was shown to be around 4 m. Fiber length shorter than 4 m (around 3.5 m or less) resulted in lasing at 1018 nm, but inadequate power absorption and high unabsorbed pump power was present in the output spectrum. Fiber lengths significantly longer than 4 m (5 m or more) did not favor any lasing action at the desired wavelength (1018 nm). We observed parasitic lasing around 1030 nm for longer active fiber length. The output end of the laser system was definitely angle cleaved to 8 ° to prevent back reflection. It should also be noted that, there was no lasing observed around 1018 nm when the output end was straight cleaved.

Our main motivation of this study is to demonstrate the development of 1018 nm YDFL with minimal efficiency variance by a pumping configuration utilizing the broadband wavelength region around 915 nm. In order to obtain the information about laser operation behavior with pumping wavelengths ranging from 902 nm to 924 nm, we have numerically analyzed our sys-

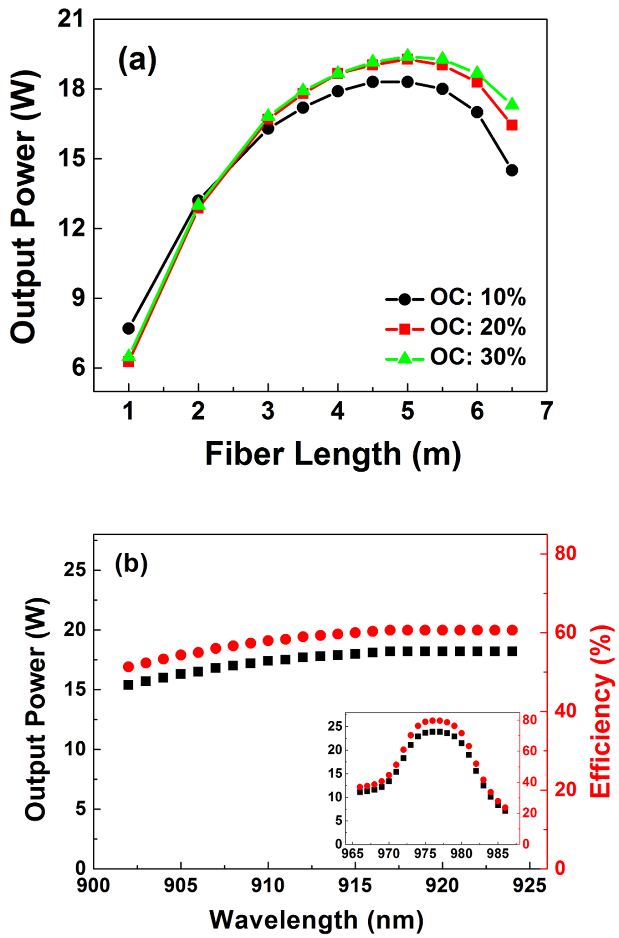

Fig. 2. (a) Numerical simulation of laser output power versus fiber lengths for three different OC-FBG reflectivities, (b) Simulation results of the output power and efficiency of the 1018 nm YDFLs while pump wavelength varies between 902 nm to 924 nm and while pump wavelength varies between 966 nm to 986 nm [1–3, 5–7] as shown in the inset **Fig.2b**. The launched power was fixed to 30 W throughout all of the numerical analysis for the sake of compatibility with the experimental work.

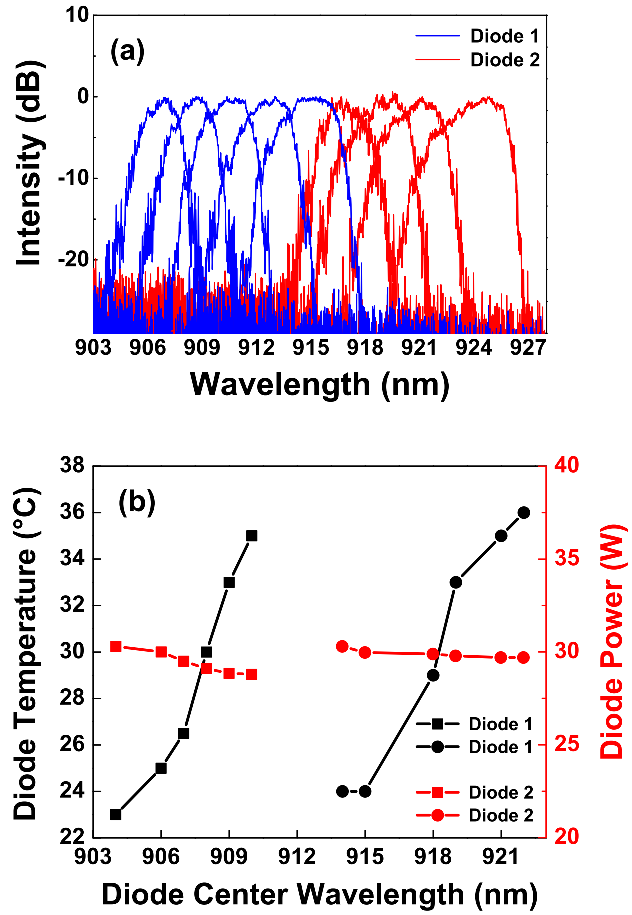

Fig. 3. (a) Optic spectrum characterization data of both Diode 1 and Diode 2 obtained at different temperature values with the help of temperature control unit. (b) Temperature and power characterization of both Diode 1 and Diode 2 with respect to the diode central wavelength from 904 nm to 922 nm.

tem. This simulation result showing in **Fig.2b** is an exact model of our experimental system with HR-FBG (99.5% reflectivity), active fiber length (4m), and OC-FBG (26% reflectivity). The simulation result shows the output power and the efficiency of the system under the pumping with central wavelengths ranging from 902 nm to 924 nm with a fixed pump power of 30 W for all pumping wavelengths. The aim of this simulation is to prove that these pumping wavelengths from 902 nm to 924 nm result a minimal output power and efficiency variation. Based on the information obtained from the simulation, laser efficiency between 59% - 61% can be obtained for the pumping configuration between 910 nm and 924 nm wavelengths. For shorter pumping wavelengths, which is between 904 nm - 910 nm, according to the simulation results laser efficiency varies between 53% - 58% at a pump power level of 30 W. Although the laser efficiency seems to be very low, it is not abnormal since the pump power level that we are working is also low for the sake of the compactness of the system. However, we have an observation from both the experiment and the simulation that as the pump power increases the efficiency will also increase accordingly. The physics behind this phenomenon is discussed and explained in the literature [14]. In most of the experimental works regarding 1018nm YDFLs, pump sources around 976 nm are frequently used, due to higher absorption cross section in Yb-doped fiber compared to 915 nm wavelength. Nevertheless, the viable pumping wavelength range is very narrow thus offers very low tunability as the simulation predicts (inset **Fig.2b**). The simulation is modeled after an optimized system with the active fiber being Nufern LMA 30/250 HI-8 with cladding absorption of 6.3 dB/m near 976 nm, and 2.1 dB/m at 915 nm. The length of the active fiber was optimized to be 3 m and the OC-FBG was chosen to be 10% (as used in [1–3, 5–7]) and input launched pump power was maintained at 30 W. The simulation shows the behavior of the model system when pumped with wavelengths from 966 nm through 986 nm. The results show that the viable pumping wavelengths, efficiency-wise, are around 971 nm – 982 nm since other wavelengths yielded an efficiency less than 50%. This viable pumping range is a 10 nm wavelength span compared to the more than 20 nm span tunability of pump sources around 915 nm.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Based on the information obtained from numerical simulations and the capabilities of our pump diodes, we were able to test 1018 nm YDFL with pump wavelengths from 904 nm to 924 nm. The optical spectra of both Diode 1 and Diode 2 are shown in **Fig.3a**. Five data points for Diode 1 and 4 data points for Diode 2 were chosen to indicate that these two diodes are able to span the wavelength region between 904 nm and 924 nm. For that purpose, optical spectrum data of both 'Diode 1' and 'Diode 2' were taken with respect to operating temperature of diodes with the help of temperature unit which is established as indicated in **Fig.1**. Alternating the operating temperature of pump diodes allows the change in the central wavelengths of pump diodes steadily even at a fixed input driving diode current. This feature has provided us to have nearly constant pump power at different pump wavelengths. We have characterized the pump diodes with respect to the pump central wavelength and pump power at each temperature value as seen in **Fig.3b**. We have observed that varying the operating temperature (within safety limits) of the diodes causes the pumping power of the diodes to slightly vary. Due to this reason, we have calculated the optical-to-optical efficiencies of the laser system at each pump center wavelength with these slightly shifted power values for the sake of exactness as shown in **Fig.4**.

The increase in the operating temperature of the diode due to limited cooling causes a red shift in the central wavelength of the diode. Diode 1 presented an initial operation wavelength of 904 nm and 30.3 W power at about 22 °C operating temperature. When its operating temperature was run up to about 34 °C, the central wavelength shifted to 910 nm and the diode output power dropped to 28.8 W. Diode 2 present an initial operation wavelength of 914 nm and power of 30.3 W at 24 °C, ended up

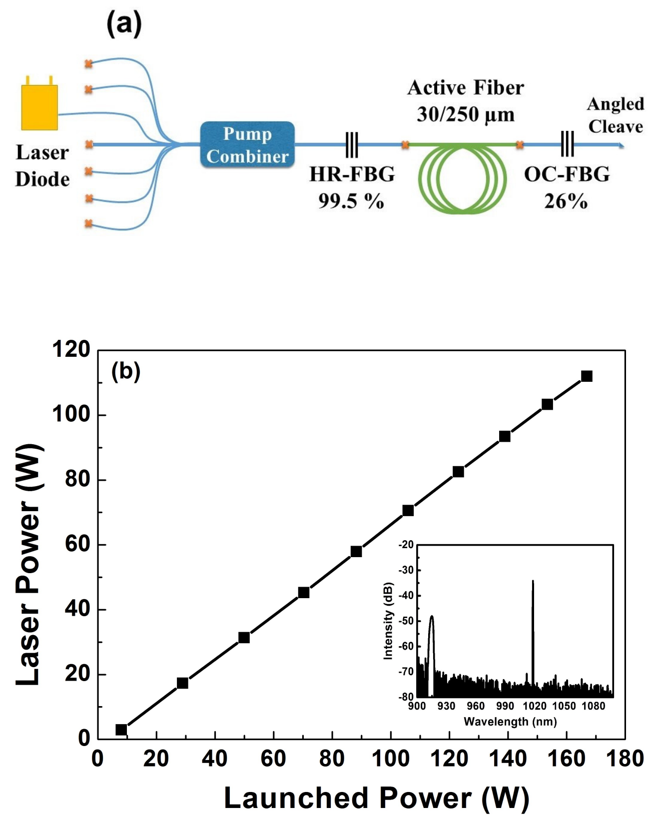

Fig. 5. (a) Schematic of the experimental setup of the 1018 nm YDFL pumped by tunable pump sources around 915 nm including HR-FBG, OC-FBG, active fiber and the angle-cleaved output end (b) Launched pump power versus laser power graph and the optical spectrum graph at maximum power shown inset.

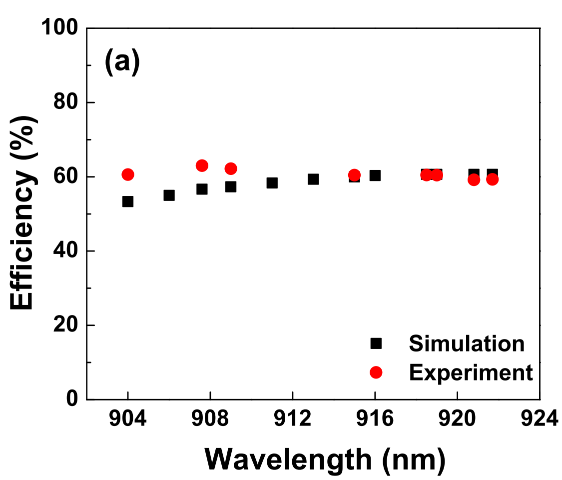

Fig. 4. Experimental and simulation results of the optical-to-optical efficiencies for pumping configurations from 904 nm to 922 nm.

with a center wavelength of 922 nm and 29.7 W at 36 °C when its operating temperature was allowed to rise. The wavelength range obtained from the characterization study formed the tunable viable wavelength span used in our experiments. The full width half maximum (FWHM) of the optical spectra of pump diodes have bandwidths which lie in between 1.2 nm and 1.3 nm for all operation temperatures; concluding narrow bandwidth enough for efficient pumping of the fiber laser system. Having analyzed and controlled the temperature of the pump diodes, we have built laser system with this tunable pumping system from 904 nm to 924 nm and consequently the experiments yielded an almost constant optical-to-optical efficiency of around 59% - 63%. The slight variation observed in the experimental efficiency graph shown in **Fig.4a** is caused by the small amount of fluctuations in the pump power of pump diodes as depicted in **Fig.3b** as mentioned above. Apart from that, this experimental result agrees with our simulation data which is shown in **Fig.2b**. The simulation data used for comparison are chosen from our earlier simulation in **Fig.2b** to match relevant points with the experimental data. As understood from the experimental results, indeed it shows the tunability of the pump sources we have used in the experiment. During this study, 30 W pump power was chosen to be a reference power level for both simulation and experimental work to show the tunability of the pump sources we have used in our configuration and the less efficiency drop at these broad pump wavelength region between 904 nm and 924 nm.

Finally, 1018 nm YDFL was tested to achieve high power level above 100 W. The schematic of the high power experiment setup is illustrated in **Fig.5**. For that purpose, Diode 1 was used as a pump source since its central wavelength at its maximum power is close to 915 nm wavelength. After that, it was integrated to a pump combiner. In spite of using just one diode laser in the system, implementing a pump combiner was necessary to preserve diode laser. Then, the cavity was completed with the same FBG pair used in the previous setup having 99.5% and 26% reflectivities. As an active medium 3 m long Liekki-Yb700 active fiber was chosen. 1018 nm fiber laser constructed with the equipments mentioned above yielded an optical-to-optical efficiency of 67.1% and a slope efficiency of 69.3% with a FWHM of 0.27 nm. The total pump power was 167 W and obtained output laser power without unabsorbed pump power was 112 W. (see **Fig.5b**). The optimal fiber length for Liekki-Yb700 active fiber was decided as 3.5 m to 4 m based on both simulation and experimental results. However, 3 m long active fiber was implemented for this experiment and thus an optic spectrum with minimum ASE was achieved. The peak-to-peak ASE suppression around 45 dB as illustrated in inset of **Fig.5b**. No parasitic lasing was observed in the output spectra of the system. The unabsorbed pump power for the laser system was estimated as one tenth of the laser power at maximum pump power. Since we have read 124 W from power meter; therefore, approximately 112 W of 124 W is 1018 nm laser power and the rest of it was unabsorbed pump power. Since the unabsorbed pump power level is slightly higher than the optimized one the laser efficiency is obtained as 67%; however, if a bandpass filter is employed in the cavity and parasitic lasing lasing between 1030 nm and 1040 nm is prevented longer active fibers can be used with a better performance. Therefore, unabsorbed pump power is lowered and optical-to-optical efficiency could reach up to 75%.

5. CONCLUSION

In conclusion, a different approach for pumping YDFL with 1018 nm output was implemented taking advantage of the wide absorption spectrum of Yb-doped fibers around 915 nm. Two YDFLs were developed, one with pump source ranging from 904 nm to 914 nm while the other from 915 nm to 922 nm. HR-FBG of 99.5% and OC-FBG of 26% were used with 30/250 µm LMA Yb-doped active fiber with absorption of 2.2 dB/m around 920 nm. With the tunable spectrum pumping scheme, it was demonstrated that there was minimal efficiency drop when pumping within the aforementioned spectral range. Optical-to-optical efficiencies of around 60% were obtained across the spectrum used for pumping at the pump power level of 30 W. The obtained laser outputs also showed good ASE suppression. Improvements to the system can be realized by using active fibers with higher Yb doping concentrations of similar geometry to the fibers used in this experiment with an optimized fiber length. Although a 1018 nm output YDFL would benefit from active fibers with lower doping concentrations [10], but, since we will be pumping from a broad region with where Yb absorption is much lower than that of 976 nm, using a highly doped Yb active fiber will produce a similar single pass gain in the laser cavity. Finally, we have performed high power experiment for our 1018 nm fiber laser system. As a result, 112 W output power with 67% optical-to-optical efficiency was obtained. In this work, 1018 nm fiber laser with 915 nm pumping configuration was demonstrated for the first time.

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