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Evaluation of 976 nm Multimode Single Emitter Laser Diodes for Efficient Pumping of 100 W+ Yb-doped Fiber Laser

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ABSTRACT

Experimental evaluation of spectral and power-current (P-I) characteristics of fiber coupled single emitter multimode laser diodes used for development of efficient pumping assembly is reported. Fiber coupled laser diodes emitting around 976 nm are best suited for pumping Yb-doped fiber lasers because of excellent coupling efficiency and reduced thermal load. We have experimentally investigated emission spectrum of fiber coupled multimode laser diodes at different temperatures and drive currents. It is found that peak emission wavelength shifts towards the longer wavelength with increase in temperature and drive current. P-I characteristics of fiber coupled laser diodes have been obtained and presented for drive current from 0.4 A to 11.5 A. Based on experiment, we have constructed spectrally matched laser diode assembly for efficient pumping of 100 W fiber laser. It requires very precise control of temperature and drive current to maintain the emission spectrum. Total 162 W power is pumped in to the Yb-doped fiber laser cavity through multi-mode pump combiners and we have obtained 110 W fiber laser output power @1070 nm. The achieved optical-to-optical efficiency is 68 per cent.

Keywords: Laser diode; Fiber laser; High power lasers; Yb-doped fiber laser

1. INTRODUCTION

Fiber lasers having all optical fiber configuration are rapidly increasing and shown good promise in defence and industrial applications. The benefits of fiber laser are high beam quality with alignment insensitivity, high efficiency and low operating cost. They are available in light weight, small packages requiring no maintenance. In kilowatt class power ranges only fiber laser provides excellent beam quality with alignment insensitivity. High power fiber lasers (HPFL) has the potential to become one of the principal HPL technologies for directed energy weapons (DEW) applications because of proven advantages in compactness, reliability, efficiency and above all good inherent beam quality.

Rare-earth-doped fiber lasers with many attractive features like high conversion efficiencies, good beam quality and light weight have recently emerged as potential candidates for most of the industrial and defence applications[1,2,3]. Ytterbium doped fiber lasers (YDFLs) are commonly employed for high power defence applications. More specifically ytterbium doped fibers offer high output powers and tunable over a broad range of wavelengths, from around 975 nm - 1100 nm (typically around 1060 nm)[4,5]. This provides a large window for combining several high power fiber lasers through spectral beam combining (SBC). Due to presence of only single excited state in Yb, it is not affected by the complications arising from excited state absorption (ESA) and is relatively immune to self-quenching processes. Consequently high concentrations of Ytterbiumions can be incorporated while maintaining excellent conversion efficiencies (typically greater than 75 per cent)[5,6]. Ytterbium also has a relatively small quantum defect, that is the pump wavelength (typically 915 nm - 975 nm) close to the lasing wavelength and very little energy is lost as heat. For pumping of Yb-doped fiber laser, fiber coupled laser diodes emitting at 976 nm is most preferred choice.

The demand of high brilliance, high power diode lasers emitting from 790 nm to 980 nm has seen a tremendous rise in the last decade. This is due to suitability of diode lasers for pumping of high power fiber laser and solid state lasers for defence as well as civil applications like large scale material processing and manufacturing of consumer electronics. The laser diodes having high power and high brightness are needed for efficient pumping of high power (kilowatt class) continuous wave (CW) fiber lasers in order to obtain high-performance with reduced manufacturing cost[7]. Fiber coupled laser diodes (FCLDs) based on multiple single emitters (MSEs) or bar can be used for pumping of kW class fiber lasers.

Micro-channel cooled High-power diode laser bars have shown very good high power and high brightness performance desired for fiber laser pumping. However, the long term performance and reliability of these bars are significantly affected by cooling water rate flow, conductivity of water, cleanliness of water and water stagnation period in micro-

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channel. Due to continuous water flow, micro-channel is corroded with time and ions are deposited in the channel. This leads to degraded thermal resistance of channel causing increase in junction temperature. Increased junction temperature shifts the emission wavelength and significantly reduces output power which eventually leads to diode failure[8].

Conductively cooled diode laser bars are next developed to overcome the drawbacks of micro-channel cooled bars and provide the high output power with straightforward cooling requirements and improved reliability. Single-emitter based architectures provide improved overall brightness and low cost compared to conductively cooled bars[7,8].

Single emitter laser diode systems provide best laser diode performance and reliability. Very high power levels with unparalleled brightness are available with facet passivated, long cavity diode lasers. The series connection of the diode lasers reduces the operating current enabling rapid power adjustments and pulsed operation while preserving diode reliability. They can be packaged in an environmentally sealed box providing decreased package induced failure (PIF)[7,8].

Development of techniques for efficiently coupling multiple emitters into a single fiber and improved diode laser brilliance has increased amount of power coupled into a single 105 µm fiber up to 100 W[9,10]. Multiple emitter fiber-coupled modules consisting of several single emitter broad area lasers (BALs) are the building block for pump modules for industrial and defense fiber laser systems due to their high brightness, excellent reliability, low production cost and high optical-to-optical efficiency[7-10].

Theoretical studies shows that Yb-doped fiber laser pumped with broad spectral width (< 5 nm) non-wavelength stabilised laser diode assembly have 70 per cent optical-to-optical efficiency for 14.5 m active fiber length. However for optimum active fiber length of 17 m optical-to-optical efficiency reaches up to 80 per cent.

This paper brings out concentrated efforts on experimental evaluation of emission spectrum and P-I characteristics of 9 W fiber coupled single emitter laser diodes. The paper investigated and presented the effect of temperature and drive current on peak emission wavelength of laser diode. The details of P-I characteristics of laser diode are also given. One of the scopes of experimentation is to select spectrally matched laser diodes. Development and optimisation of laser diode assembly for pumping of 100 W Yb-doped fiber laser is described. Integration of pumping assembly with laser cavity is given and results are reported.

2. EXPERIMENTAL DETAILS

Development of pumping assembly requires exhaustive experimental investigation of laser diode. Temperature and drive current tuning is performed to obtain desired results. We have investigated emission spectrum and P-I characteristics of 30 laser diodes prior to construction of spectrally matched pumping assembly. Schematic for spectral and P-I characteristics evaluation of fiber coupled diode laser is presented in Fig. 1.

A fiber coupled laser diode is tightened on the top of thermo electric cooling (TEC) cold plate. The high conductivity graphite sheet is used as the thermal interface material between

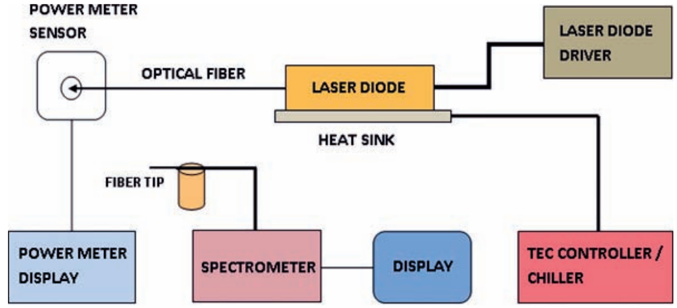


Figure 1. Schematic of an experimental setup used for evaluation of laser diode.

the backside of the laser diode package and the top surface of the cold plate to minimize contact thermal resistance. The laser diode is driven by commercially available cw laser diode driver from TDK Lambda/Lumina Inc. The drive current can be varied from 0-12A. The laser diode output is available through 105/125 µm fiber (NA 0.22). The output laser beam is made to fall on sensor head and transferred to an optical power meter. The scattered radiation is collected by charge coupled device (CCD) spectrometer through optical fiber and obtained spectrum is displayed on laptop. Photograph of experimental set-up is shown in Fig. 2.

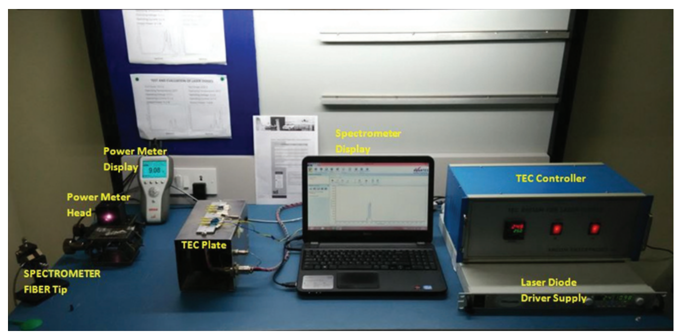


Figure 2. Experimental set-up.

The package temperature is measured using a thermocouple based digital thermometer. The package temperature is controlled by a TEC cooling system having <±1 °C temperature stability. Uncooled thermal camera FLIR A-310 is used to monitor the real time temperature profile of laser diode and cooling plate. The results from thermal camera and thermo-couple were found to be in corroboration with each other. It can measure temperature from 0 °C to 120 °C with resolution of 0.1 °C. In this way we have reliably monitored the temperature.

3. RESULTS AND DISCUSSIONS

We have evaluated 30 laser diodes for their P-I and spectral characteristics. P-I characteristics of one laser diode, emission peak variation with drive current is also obtained for this laser diode and temperature effect on emission peak is also recorded for a different laser diode, and they are disussed in later sections.

3.1 P-I Characteristics

The optical power of fiber coupled laser diode is measured as a function of the driving current (I) and the corresponding curve, referred as the power-current (P-I) curve, is obtained. Figure 3 shows the P-I curves of laser diode at different driving currents starting with 0.4 A to 11.5 A. The threshold current is 0.5 A. With increase in temperature, losses inside the laser cavity enhanced due to non-radiative recombination, leading to decrease in output power[12]. The P-I curve depicted in Fig. 3 is specified at 25 °C.

Maximum output power obtained at 11.5 A is > 9 W having peak emission around 976 nm at 25 °C. Maximum electrical to optical efficiency of laser diode (ex fiber) obtained is > 50 per cent. However, efficiency decreases up to 43.5 per cent at maximum output power. Figure 4(a) present variation of laser output power with electrical input power. The electrical efficiency with laser output power is depicted in Fig. 4(b).

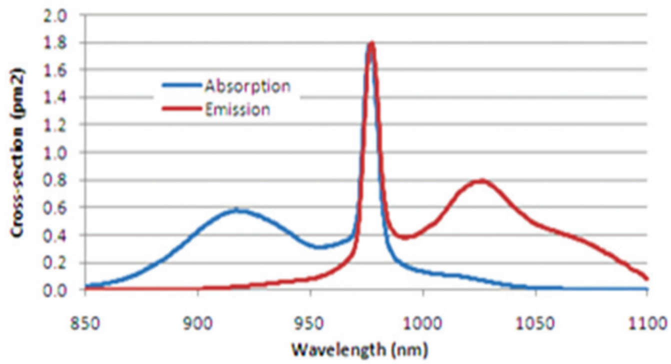
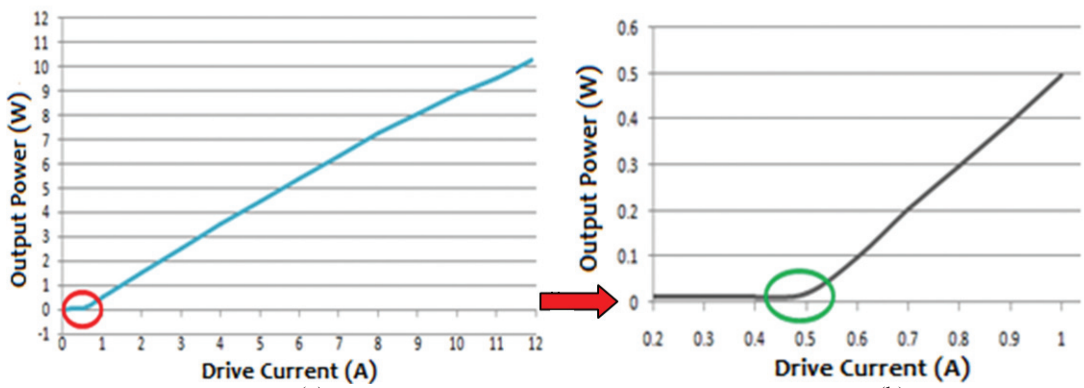
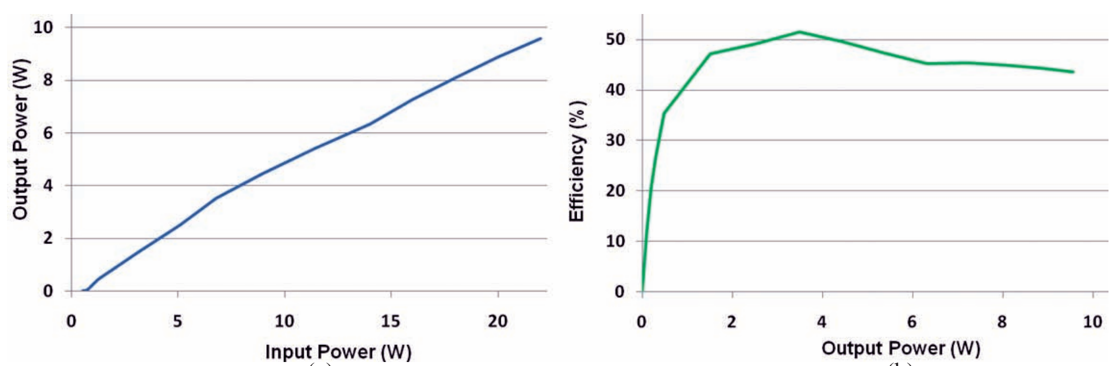


Figure 5. Active fiber with absorption and emission spectrum.



(a) (b)

Figure 3. (a) P-I Characteristics and (b) Threshold region.



(a) (b)

Figure 4. (a) Output power vs input power and (b) Efficiency vs output power.

3.2 Spectral Characteristics

The emission spectrum of laser diodes is the most important design parameter for diode pumped fiber lasers. Absorption and emission cross-sections of Nufern Gen-VIII Yb-doped active fiber are as shown in Fig. 5.

From the absorption spectrum of Yttrium(Yb^{3+}) doped fiber (Nufern) it is found that its peak absorption is at around 976 nm. Thus we have chosen 976 nm laser diodes (InGaAs) for pumping of Yb-doped fiber laser. Ideally laser diode must emit at single wavelength (say 976 nm) so that all the emitted power is absorbed. But practically it is not possible. We have evaluated 30 laser diodes at three temperatures (15 °C, 20 °C, 25 °C) and obtained the spectra. Temperature dependent emission spectrum of one of laser diode is shown Fig. 6.

It can be seen that as temperature increases peak wavelength shifts toward longer wavelength due to decrease in band-gap energy with temperature. Results show the emission peak wavelength of laser shifts around 4 nm (972.5 nm to 976.5 nm) for 10 °C increase in temperature (15 °C to 25 °C) giving a wavelength temperature co-efficient of 0.4 nm/°C. These results are closely matching with reported wavelength temperature co-efficient data for InGaAs free-running laser diodes. The intensity of lasing spectra also reduces with increase in temperature. The increase of temperature causes the increasing internal and external loss at active region. These losses are associated with the increase in carrier leakage and non-radiative recombination at defects in the active layer. This phenomenon consequently results in the reduction of the intensity[11].

Variation in emission spectrum with drive current for laser diode is given in Fig. 7. P-I characteristics of this laser diode is given in section 3.1. Emission peak also shifts with drive

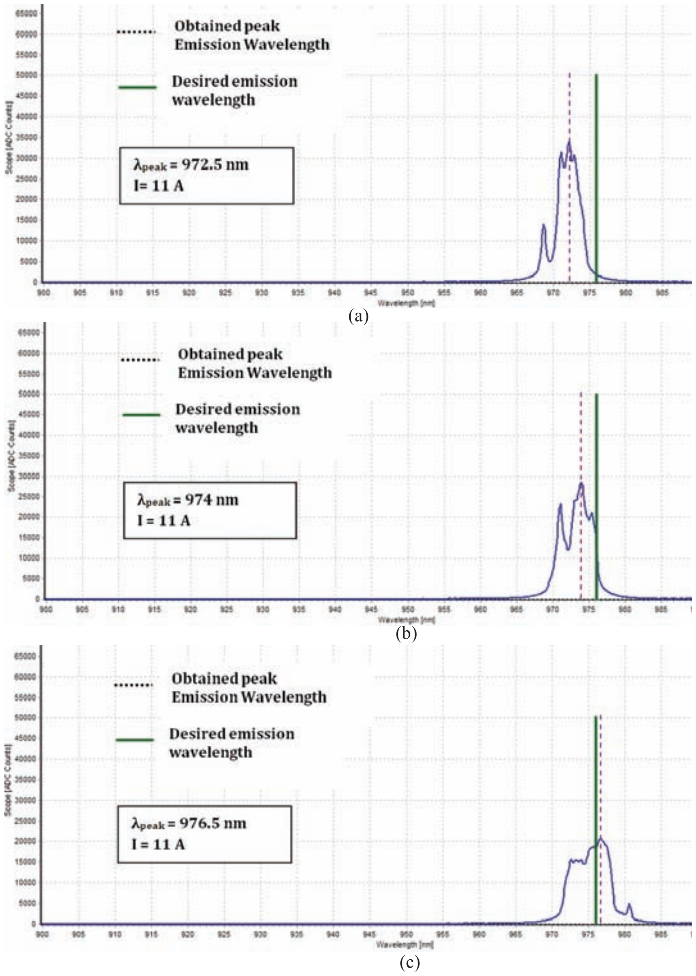


Figure 6. Emission spectrum at (a) 15 °C, (b) 20 °C, and (c) 25 °C.

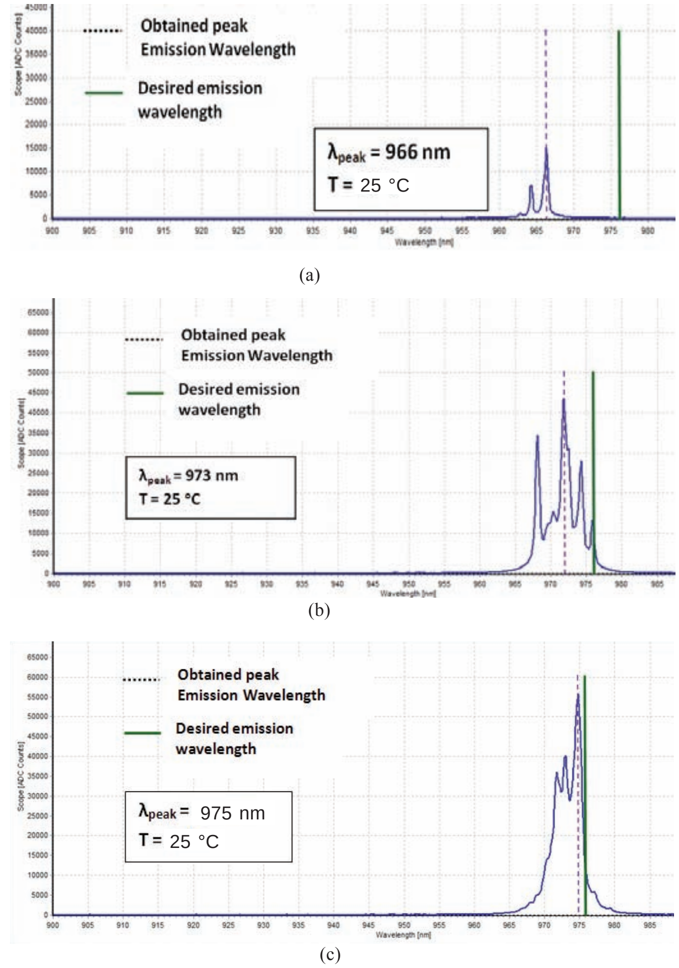


Figure 7. Drive current dependent emission spectrum: (a) (I = 0.5 A), (b) (I = 8 A), (c) (I = 11.5 A).

current. Peak emission wavelength (T = 25 °C) at threshold current (0.5 A) is 966 nm and shifts to 975 nm at 11.5 A.

3.3 Integration

Based on emission spectrum and P-I characteristics, we have selected 18 laser diodes having matching characteristics for development of pumping assembly. We have constructed 3 sets of 6 laser diodes each having nearly matching characteristics and mounted them on 3 water cooled plates. The electrical-to-optical efficiency of laser diode is around 45 per cent. So around 11 W power is dissipated as heat by each 9W laser diode. Total heat dissipation per plate is 11 x 6 = 66 W. The water temperature is maintained at around 23 °C. This maintains aluminium plate temperature at around 23 °C at the start of laser operation. As soon as laser diodes start working, the temperature of plate starts rising. The plate temperature stabilises at around 24 °C which in-turn keep diode base temperature at around 25 °C which is required for optimised performance of laser diode assembly. Each set is connected to separate laser diode driver in order to obtain real time drive current tuning to get optimised output power & emission spectrum. The basic optical schematic for fiber laser is shown in Fig. 8.

The cavity consists of 14.5 meter length active 20/400 large mode area (LMA) fiber spliced to the two Fiber Bragg Grating (FBG) mirrors. The pump power at 976 nm is introduced into the cavity through the high reflecting FBG mirror. Four laser diodes are spliced to one 4x1 combiner. Five numbers of 4 x 1 pump combiners are used to combine the power from 18 laser diodes. Output power and emission spectrum of each 4 x 1 pump combiner is obtained prior to splicing with (6+1)x 1 combiner. Output power from 4 combiners is around 36 W each. Output power from fifth 4 x 1 combiner is 18 W because only two laser diodes are used. Spectrally matched emission spectrum of two 4x1 combiners having peak emission wavelength at around 976 nm is given in Fig. 9(a) and (b).

Real time drive current tuning is done to obtain emission spectrum of all 5 combiners having peak emission wavelength at around 976 nm. Output of five 4 x 1 combiners is spliced to five input legs of (6+1) x 1 combiner to get total input pump power up to 162 W from 18 laser diodes. Total 162 W power was pumped in to the fiber laser cavity and obtained 110 W fiber laser output power @1070 nm. The optical-to-optical efficiency of the system is 68 per cent. Output spectrum shows laser beam at 1070 nm having no other emission peak as expected. Figure 10 shows the details of developed system. Figure 11 depicts single mode beam profile of output beam having $M^2 = 1.2$.

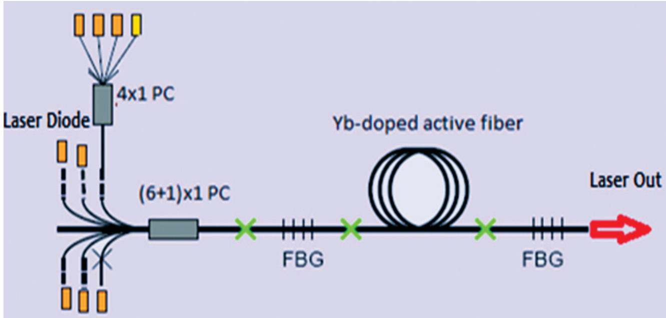


Figure 8. Basic optical scheme of fiber laser.

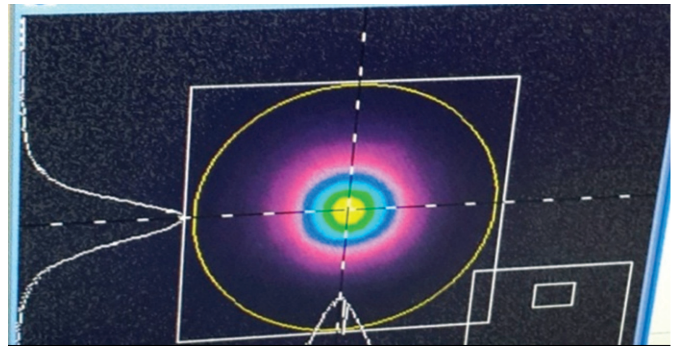
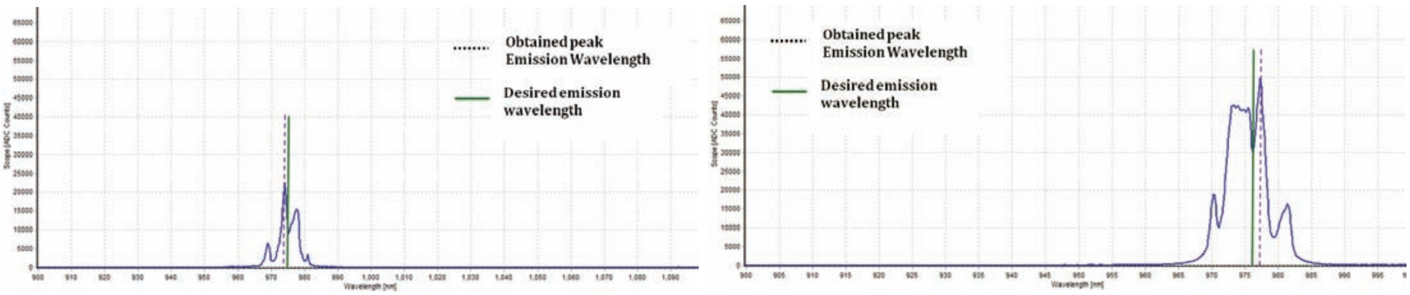
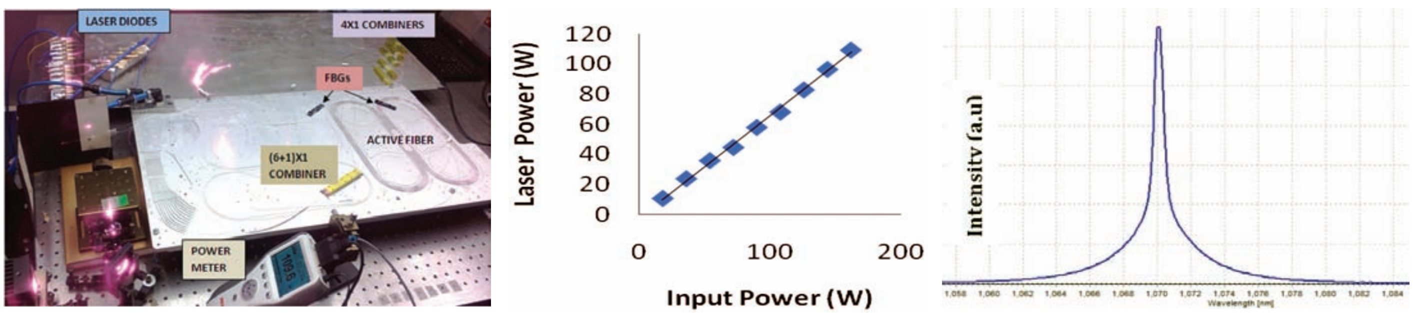


Figure 11. Beam profile.



(a) (b)

Figure 9. (a) Emission spectrum of first 4x1 combiner and (b) Emission spectrum of second 4x1 combiner.



(a) (b) (c)

Figure 10. (a) Experimental setup of developed 100 W fiber laser, (b) Laser power *vs* pump power, and (c) Output spectrum.

4. CONCLUSION

The paper presented temperature and drive current effects on the spectral and P-I characteristics of 9 W fiber coupled non-wavelength stabilised laser diodes. In order to develop reliable, high efficiency fiber laser systems, wavelength stabilised laser diodes are desired. However, we have achieved spectral matching of non-wavelength stabilised laser diode pumping assembly by very precise control of temperature and drive for efficient pumping of 100 W Yb-doped fiber laser and obtained 68 per cent optical to optical efficiency.

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In the current study, he carry out analysis of some of the results presented in the paper. He has provided valuable suggestions and guidance during experimental work.