

# Multi-watts narrow-linewidth all fiber Yb-doped laser operating at 1179 nm

Mridu P. Kalita,<sup>1,2</sup> Shaif-ul Alam,<sup>1</sup> Christophe Codemard,<sup>1</sup> Seongwoo Yoo,<sup>1</sup> Alexander J. Boyland,<sup>1</sup> Morten Ibsen,<sup>1</sup> and Jayanta K. Sahu<sup>1,3</sup>

<sup>1</sup>Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ UK  
<sup>2</sup>mpk@orc.soton.ac.uk,  
<sup>3</sup>jks@orc.soton.ac.uk

**Abstract:** An all-fiber, narrow-linewidth, high power Yb-doped silica fiber laser at 1179 nm has been demonstrated. More than 12 W output power has been obtained, corresponding to a slope efficiency of 43% with respect to launched pump power, by core-pumping at 1090 nm. In order to increase the pump absorption, the Yb-doped fiber was heated up to 125°C. At the maximum output power, the suppression of amplified spontaneous emission was more than 50 dB. Furthermore, theoretical work confirms that the proposed laser architecture can be easily scaled to higher power.

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## References and links

1. C. E. Max, S. S. Olivier, H. W. Friedman, K. An, K. Avicola, B. V. Beeman, H. D. Bissinger, J. M. Brase, G. V. Erbert, D. T. Gavel, K. Kanz, M. C. Liu, B. Macintosh, K. P. Neeb, J. Patience, and K. E. Waltjen, "Image improvement from a sodium-layer laser guide star adaptive optics system," *Science* **277**(5332), 1649–1652 (1997).
2. N. S. Sadick, and R. Weiss, "The utilization of a new yellow light laser (578 nm) for the treatment of class I red telangiectasia of the lower extremities," *Dermatol. Surg.* **28**(1), 21–25 (2002).
3. S. D. Jackson, F. Bugge, and G. Erbert, "Directly diode-pumped holmium fiber lasers," *Opt. Lett.* **32**(17), 2496–2498 (2007).
4. S. Sinha, C. Langrock, M. J. F. Digonnet, M. M. Fejer, and R. L. Byer, "Efficient yellow-light generation by frequency doubling a narrow-linewidth 1150 nm ytterbium fiber oscillator," *Opt. Lett.* **31**(3), 347–349 (2006).
5. J. Ota, A. Shirakawa, and K. Ueda, "High-power Yb-doped double-clad fiber laser directly operating at 1178nm," *Jpn. J. Appl. Phys.* **45**(4), L117–L119 (2006).
6. A. S. Kurkov, V. M. Paramonov, and O. I. Medvedkov, "Ytterbium fiber emitting at 1160 nm," *Laser Phys. Lett.* **3**(10), 503–506 (2006).
7. A. S. Kurkov, "Oscillation spectral range of Yb-doped fiber lasers," *Laser Phys. Lett.* **4**(2), 93–102 (2007).
8. R. Goto, K. Takenaga, K. Okada, M. Kashiwagi, T. Kitabayashi, S. Tanigawa, K. Shima, S. Matsuo, and K. Himeno, "Cladding-pumped Yb-doped solid photonic bandgap fiber for ASE suppression in shorter wavelength region," in *Optical Fiber Communication Conference 2008, Technical Digest (CD)* (Optical Society of America, 2008), paper OTuJ5.
9. V. V. Dvoyrin, V. M. Mashinsky, O. I. Medvedkov, and E. M. Dianov, "Yellow Frequency-Doubled Self-Heated Yb Fiber Laser," in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies*, OSA Technical Digest (CD) (Optical Society of America, 2008), paper CWB5.
10. A. Shirakawa, H. Maruyama, K. Ueda, C. B. Olausson, J. K. Lyngsø, and J. Broeng, "High-power Yb-doped photonic bandgap fiber amplifier at 1150–1200 nm," *Opt. Express* **17**(2), 447–454 (2009).
11. R. Goto, E. C. Magi, and S. D. Jackson, "Narrow-linewidth, Yb<sup>3+</sup>-doped, hybrid microstructured fibre laser operating at 1178 nm," *Electron. Lett.* **45**(17), 877–878 (2009).
12. D. Georgiev, V. P. Gapontsev, A. G. Dronov, M. Y. Vyatkin, A. B. Rulkov, S. V. Popov, and J. R. Taylor, "Watts-level frequency doubling of a narrow line linearly polarized Raman fiber laser to 589nm," *Opt. Express* **13**(18), 6772–6776 (2005).
13. M. P. Kalita, S. Yoo, and J. K. Sahu, "Influence of cooling on a bismuth-doped fiber laser and amplifier performance," *Appl. Opt.* **48**(31), G83–G87 (2009).
14. Y. Feng, L. Taylor, and D. Calia, "25 W Raman-fiber-amplifier-based 589 nm laser for laser guide star," *Opt. Express* **17**(21), 19021–19026 (2009).
15. M. P. Kalita, S. Yoo, and J. K. Sahu, "Bismuth doped fiber laser and study of unsaturable loss and pump induced absorption in laser performance," *Opt. Express* **16**(25), 21032–21038 (2008).
16. A. B. Grudinin, D. N. Payne, P. W. Turner, L. Nilsson, M. N. Zervas, M. Ibsen, and M. K. Durkin, "An optical fiber arrangement," W.O. patent 00/67350 (Nov 9, 2000).

17. X. Peng, and L. Dong, "Temperature dependence of ytterbium-doped fiber amplifiers," *J. Opt. Soc. Am. B* **25**(1), 126–130 (2008).
  18. A. B. Wojcik, K. Schuster, J. Kobelke, C. Chojetzki, C. Michels, K. Rose, and M. J. Matthewson, "Novel hybrid glass protective coatings for high temperature applications," *Proc. 54th Int. Wire & Cable Symp.* 368 (2005).
  19. <http://www.fibercore.com>
  20. [http://www.optiwave.com/products/system\\_overview.html](http://www.optiwave.com/products/system_overview.html)
  21. C. R. Giles, and E. Desurvire, "Modeling erbium-doped fiber amplifiers," *J. Lightwave Technol.* **9**(2), 271–283 (1991).
  22. J. Koponen, M. Söderlund, H. J. Hoffman, D. A. Kliner, J. P. Koplow, and M. Hotoleanu, "Photodarkening rate in Yb-doped silica fibers," *Appl. Opt.* **47**(9), 1247–1256 (2008).
  23. G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. (Academic Press, San Diego, 2001).
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## 1. Introduction

Yb-doped silica fiber is an extremely successful gain medium that operates efficiently in the wavelength region of 1030–1100 nm, with excellent beam quality and multi kilowatt of output power level; which finds many applications in material processing, spectroscopy, medicine etc, to name a few. Lately, considerable attention has been paid to extend the useable wavelength range of Yb-doped fiber beyond 1100 nm. Compact, high power, high brightness source at 1178 nm is of great interest for frequency doubling to 589 nm for laser guide star generation [1], spectroscopy and medicine [2]. Moreover, fiber laser emitting at the 1.1–1.2  $\mu\text{m}$  wavelength range can also be used as a pump source for holmium and thulium doped fiber lasers operating in the 2.0  $\mu\text{m}$  eye safe region [3].

Different approaches have been proposed to operate Yb-doped fiber lasers in the long wavelength (1160–1180 nm) range [4–11]. Because the emission cross-section of Yb-doped aluminosilicate fibre extends up to 1200 nm, using conventional Yb-doped fiber, an output of 121 mW at 1150 nm was achieved with a slope efficiency of 21%, by pumping at 977 nm [4]. By employing a high-Q resonator design in conjunction with a double clad Yb-doped fiber, up to 6.5 W output at 1178 nm was also obtained [5]. Another approach includes core pumping of a Yb-doped fiber at 1070 nm with simultaneous heating of the fiber above 70°C to improve the emission cross-section [6]. The maximum slope efficiency, with respect to pump power was 45% at 1160 nm, with a maximum output power of 3.3 W. However, the low emission cross section at these wavelengths and the gain competition from shorter wavelengths, especially in the 1030–1100 nm wavelength range, leads to the generation of amplified spontaneous emission (ASE) and parasitic lasing at high pump power limiting the utilizable gain and power scaling, making the operation a challenging work. Other alternatives have been proposed to overcome those issues, such as a cladding pumped Yb-doped solid photonic bandgap fibers for suppression of ASE at 1030 nm [8]. Also, by using the spectral filtering properties of photonic bandgap fibers, with a Raman fiber laser seeded MOPA configuration, 32 W output at 1156 nm and 30 W output at 1178 nm has been realized [10]. However, complex system structure and therefore difficult fabrication conditions with the additional possibility of photodarkening, when pumped at 915–976 nm; make such a laser impractical for industrial use. In another work, Goto et al. reported a narrow linewidth Yb-doped hybrid microstructured fiber, but the output power was limited due to high loss present in the fiber [11]. Other possibilities are Raman fiber laser [12] and bismuth-doped fiber laser and amplifier [13]. Narrow-linewidth amplification in Raman fiber amplifier is difficult because of stimulated Brillouin scattering. Thus in [14], the outputs of two Raman fibre amplifiers are coherently combined together and as a result, the configuration is complex and difficult to implement. In the case of bismuth doped fiber laser, the reported efficiency is low due to the presence of high unsaturable loss [15].

In this paper, we report an all-fiber, high power, narrow-linewidth Yb-doped silica fiber laser operating at 1179 nm, when core pumped at 1090 nm, and heated at 125°C. Using numerical simulation, we have shown that the output power can be scaled up at 1179 nm with optimized laser cavity. The results described in this paper are particularly important for efficient frequency doubling for suitable laser guide star applications.

## 2. Experimental procedures

It is well known that aluminosilicate host fiber is preferable for the long wavelength generation of Yb-doped fiber [7] because of preferential cross-sections. The Yb-doped aluminosilicate fiber used in this work was fabricated in-house by modified-chemical-vapor-deposition (MCVD) and the solution doping technique. The preform was drawn into a fiber with 125  $\mu\text{m}$  outer diameter with higher index polymer coating materials. The fiber had a 10  $\mu\text{m}$  Yb-doped core diameter with an NA of 0.11. The Yb concentration in the core was estimated to be 14000 ppm-wt. The background loss in the fiber was less than 10 dB/km, measured at 1285 nm with a high resolution optical time domain reflectometer.

Figure 1 shows the schematic of the Yb-doped fiber laser experimental set up. The fiber laser consisted of a 20 m long Yb-doped fiber that is fusion spliced to a 1090-1179 nm WDM (wavelength division multiplexer) coupler. The pump power is coupled into the core of the Yb-doped fibre through the WDM coupler. The pump consists of a GTWave [16] based Yb-doped fiber laser capable of delivering up to 30 W of output power at 1090 nm. Therefore, the WDM coupler was mounted on a heat sink to remove excess heat and avoid damage during the high power operation. The other end of the doped fiber was flat cleaved and butted to a broadband mirror with high reflectivities both at the pump and signal wavelengths. A Fiber Bragg Grating (FBG), acting as an output coupler, was spliced to the 1179 nm arm of the WDM coupler to select the lasing wavelength. The reflectivity of the FBG was 61% at 1179 nm with 3 dB bandwidth of 0.25 nm. The Yb-doped fiber was placed inside an oven, which was maintained at 125°C to increase the pump absorption at 1090 nm [17].

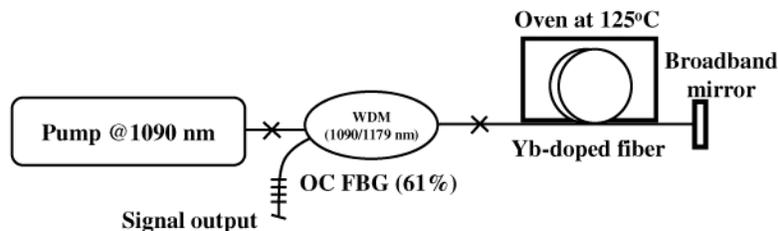


Fig. 1. Experimental setup of the 1179 nm fiber laser.

## 3. Experimental results

The absorption and emission cross sections of the fiber were measured at various temperatures ranging from 22°C (room temperature) to 125°C. It was observed that the Yb absorption at 1090 nm grows by several times when the fiber was heated to 125°C compared to that of the room temperature. The absorption cross section at room temperature was  $1.67 \times 10^{-27} \text{ m}^2$  which increases to  $4.77 \times 10^{-27} \text{ m}^2$  at 125°C. However, there was no noticeable change in the emission cross sections at the 1100-1200 nm range. The emission cross section at 1179 nm at room temperature was  $1.56 \times 10^{-26} \text{ m}^2$  while that at 125°C was  $1.69 \times 10^{-26} \text{ m}^2$ .

Figure 2(a) shows the output power of the 1179 nm fiber laser as a function of the launched pump power. A total signal output power of 12.3 W at 1179 nm was obtained for 30 W of launched pump power at 1090 nm. The slope efficiency was estimated to be 43% with respect to the launched pump power. No roll-off or saturation of the output power was observed even at the maximum available pump power, indicating that the extracted output power was limited by the available pump power. It is to be noted that the reflectivity of the output coupler FBG was not optimized; instead the fiber length was optimized for the maximum output power.

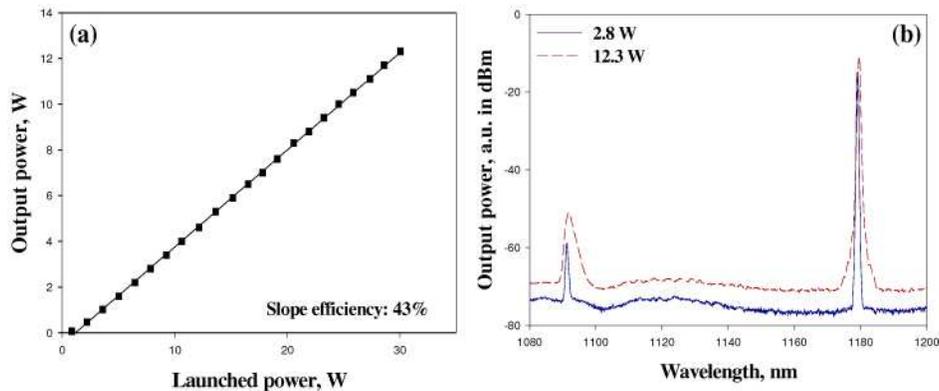


Fig. 2. (a). Output power and (b) output spectrum (taken with an optical spectrum analyzer with 0.5 nm resolution) of Yb-doped fiber laser operating at 1179 nm.

An optical spectrum analyzer (Yokogawa AQ-6370) was used to measure the output spectrum. The measured spectrum of 1179 nm laser at different output power levels is shown in Fig. 2(b). The suppression of the ASE was better than 50 dB even at the maximum output power. The 3 dB linewidth of the laser spectrum at the maximum output power was less than 0.38 nm, measured with 0.02 nm resolution (Fig. 3). The laser linewidth broadens slightly with increasing pump power as expected in typical fiber laser. Our results seem to indicate that pumping at 1090 nm helps to suppress the parasitic lasing in an Yb-doped fiber laser operating at 1179 nm.

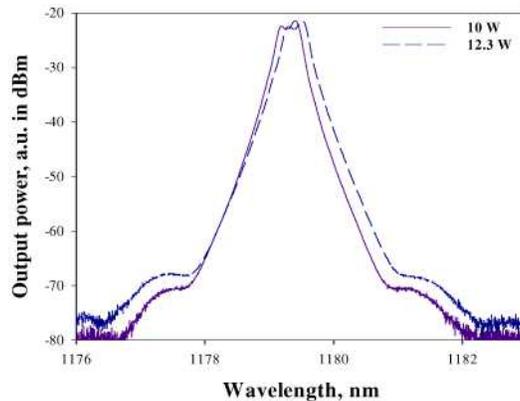


Fig. 3. Output spectrum of the fiber laser at different signal power (optical spectrum analyzer resolution 0.02 nm).

We did not observe any noticeable change in the output power over the whole set of experiment. However, the fiber strength seems to decrease after several days of operation, due to the degradation of the coating material at 125°C. The temperature handling capability of the fiber can be further improved at least up to 400°C by using hybrid glass protective coating materials [18] or by using polyimide coated fiber [19]. These coating materials of high thermal stability can offer stable and long time operation without any deterioration of the active fiber.

#### 4. Modeling of the 1179 nm laser

Following the experimental findings, we theoretically examined the optimization of the fiber laser cavity, using a commercial software (OptiSystem 8.0). The model is based on the solution of the rate and propagation equations [20, 21] of a two level system.

The measured Yb cross sections at 125°C were used for the calculations. The model was first applied to the Yb-doped fiber laser configuration described in section 2. A 20 m long Yb-doped fiber was pumped at 1090 nm with a maximum pump power of 30 W. The fiber parameters were selected to be the same as the fabricated Yb-doped fiber. With an output coupler of 61% reflectivity, a slope efficiency of 43% was obtained which clearly matched the experimental value as shown in Fig. 4(a). We did not observe any short wavelength ASE build up with the numerical model as well.

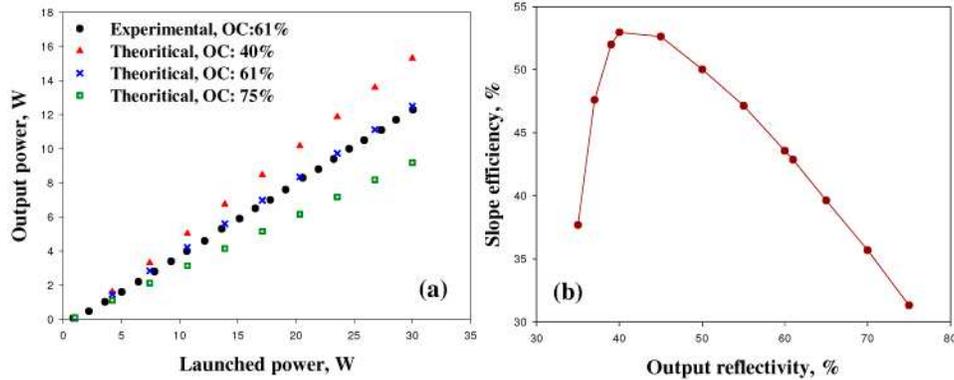


Fig. 4. (a). Output power vs. launched pump power with different output coupler transmittance, experimental and theoretical value, and (b) dependence of slope efficiency on the output coupler transmittance.

We then optimized the reflectivity of the output coupler to maximize the output power. In the first instance, the fiber length was kept constant at 20 m. The results are summarized in Fig. 4. A maximum slope efficiency of 53% with respect to launched pump power was achieved for 40% output coupler reflectivity [Fig. 4 (b)]. The corresponding output power was projected to be more than 15 W as shown in Fig. 4 (a). Figure 5 illustrates the slope efficiency as a function of fiber length for three different output coupler reflectivities. One can see that the optimum fiber length strongly depends on the coupler reflectivity.

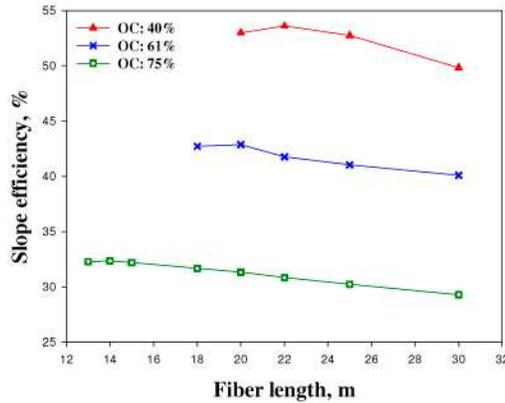


Fig. 5. Slope efficiency vs. active fiber length for different output coupler reflectivity.

The calculation of population inversion of the Yb-doped fiber in the optimized cavity shows that the population inversion along the fiber was less than 2.5% for the 1179 nm laser (Fig. 6). Photodarkening can be greatly reduced when the population inversion is low. Hence, our results suggest that potentially photodarkening effect will be negligible in the Yb-doped fiber laser [22] and therefore an output power of more than 250W is achievable before being limited by the Raman process [23].

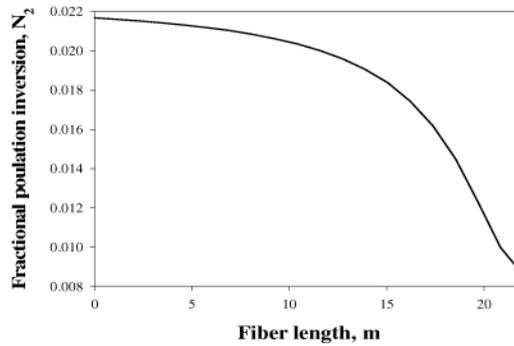


Fig. 6. Evolution of population inversion along the fiber length.

## 5. Conclusion

In conclusion, we have experimentally demonstrated a 1090 nm pumped, high power, narrow linewidth Yb-doped fiber laser operating at 1179 nm. Our simple and robust configuration is capable of generating more than 12 W output power with a slope efficiency of 43%. We have carried out numerical modelling to optimize the laser cavity as well to understand the maximum power extractable from this architecture. Numerical results suggest that the slope efficiency and hence the output power can be improved by optimizing the output coupler reflectivity. Slope efficiency as much as 53% is possible by decreasing the output coupler reflectivity from 61% to 40%. Further enhancement in output power is possible by using high power single mode pump sources at 1090 nm. The accessibility of 1090 nm fiber laser sources with hundreds of watts of output power and with the availability of high power passive optical components (e.g. WDM couplers, FBG), the proposed cavity architecture demonstrate the potential to achieve output power in excess of 250 W. This would open the door to high power yellow light sources for laser guide star applications and many more. To achieve the linewidth required for laser guide star application, a single frequency seeded master oscillator power amplifier (MOPA) configuration could be used. Furthermore, for efficient frequency doubling, polarization maintaining Yb-doped fiber would be developed. Power scaling of single frequency MOPA is usually limited by the onset of stimulated Brillouin scattering, which can be mitigated using innovative fiber design and advanced experimental techniques.

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