Widely Tunable Single-Mode Yb-Doped All-Fiber Master Oscillator Power Amplifier

Jinmeng Hu, Lei Zhang, and Yan Feng

***Abstract*— A Yb-doped linearly polarized fiber ring oscillator continuously tunable from 1000 to 1099 nm is built and amplification over the whole range is investigated with emphasis on the short wavelength regime of 1000–1025 nm. With an all-fiber single-mode polarization-maintaining master oscillator power amplifier, over 10 W output from 1010 to 1090 nm and over 30 W from 1014 to 1080 nm are achieved. At wavelength <1020 nm, bandpass filters are inserted for suppressing amplified spontaneous emission. The source can be used in a variety of applications, including laser cooling of Yb-doped solids.**

***Index Terms*— Fiber lasers, doped fiber amplifiers, laser tuning.**

I. Introduction

WAVELENGTH tunable laser sources around 1 μm have found applications in photochemistry, spectroscopy, metrology and medical treatments, *etc*. [1]. They are also frequently used as pump sources for nonlinear frequency converters to access even broader spectral regions. Yb-doped fibers' emission band ranges from 950 to 1200 nm [2], which is suitable for wavelength tunable laser operation. There are a number of reports on tunable Yb fiber laser and amplifier [1], [3]–[6]. For common wavelengths around 1060 nm, 133 W fiber amplifier was demonstrated by Hildebrandt *et al*. with a 45 nm tuning range [4]. For laser or amplifier operating at the edge of Yb gain spectrum, amplified spontaneous emission (ASE) at the center of the gain spectrum would result in spectral contamination and ultimately saturate the gain more effectively than the laser [5]. Various spectral filtering techniques are used to expand the tuning range or increase output power. Based on a diffraction-grating pair [3], and acousto-optic tunable filters [5], 10 W laser over the range of 1032-1124 nm and 1030-1110 nm are demonstrated respectively. To achieve efficient lasing at 980 nm, free space components like volume Bragg gratings [6] and large-mode-area photonic crystal rod-type fibers [1] are used. However, the main advantage of fiber laser is lost due to the use of free space components in those works.

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A less explored wavelength range for Yb-doped fiber laser is 1000 to 1025 nm. Laser at this wavelength regime has special applications in laser cooling of Yb-doped solids [7]–[9], optical lattice clock based on Yb atoms [10], laser cooling of mercury atoms [11], *etc*. 1018 nm lasers have been studied for tandem pumping of Yb-doped fiber laser [12]. A 146 W amplifier at 1009 nm was recently reported, where two rod type photonic crystal fibers are used in amplifier stages [13]. However, for the study of laser cooling of Yb-doped solids, a high power robust all-fiber laser tunable from 1010 to 1025 nm is desirable [8], [14].

In this letter, we report a widely-tunable all-fiber single-mode polarization-maintaining master oscillator power amplifier (MOPA). The Yb-doped fiber oscillator is continuously tunable from 1000 to 1099 nm. After the first amplifier, multi-watt output over the wavelength range of 1002-1099 nm is demonstrated with maximum 18.2 W at 1030 nm. With two stage amplifiers, over 10 W output from 1010 to 1090 nm and over 30 W from 1014 to 1080 nm are achieved. Note, fiber-pigtailed bandpass filters are inserted into the MOPA to suppress ASE when it operates at wavelength short than 1020 nm. The laser system is built with off-the-shelf components and all-fiber-connected, therefore, promising for many applications including laser cooling of Yb-doped solids.

II. Experimental Setup

The configuration of the tunable fiber laser system is shown in Fig. 1. Yb-doped polarization-maintaining (PM) double-clad (DC) fibers with a core diameter of 10 μm and a numerical aperture of 0.075 are used as gain media. They are pumped by 976 nm laser diodes (4.8 dB/m nominal absorption) through pump and signal combiners with pump strippers to damp the unabsorbed pump light. The master laser uses a ring cavity geometry with a 0.5 m long gain fiber. A tunable bandpass filter (T-BPF) based on thin film cavity is used to select the operating wavelength inside the cavity, which is tunable from 1000 to 1099 nm and has a tuning resolution of 0.02 nm and a bandwidth of 1 nm at 3 dB.

Two amplifier stages are built to study the amplification process from 1000 to 1099 nm and boost the power. The amplifiers are optimized for short wavelength operation. Only $\sim$ 1 m gain fiber is used in the first stage, while the gain fiber of the second stage is chosen to be $\sim$ 1.4 m long considering the larger input. When the laser system works in the range of 1000 - 1020 nm, bandpass filters are inserted to reduce the ASE at longer wavelength, whose transmission spectrum is shown in the inset of Fig. 1. The fiber output end is angle

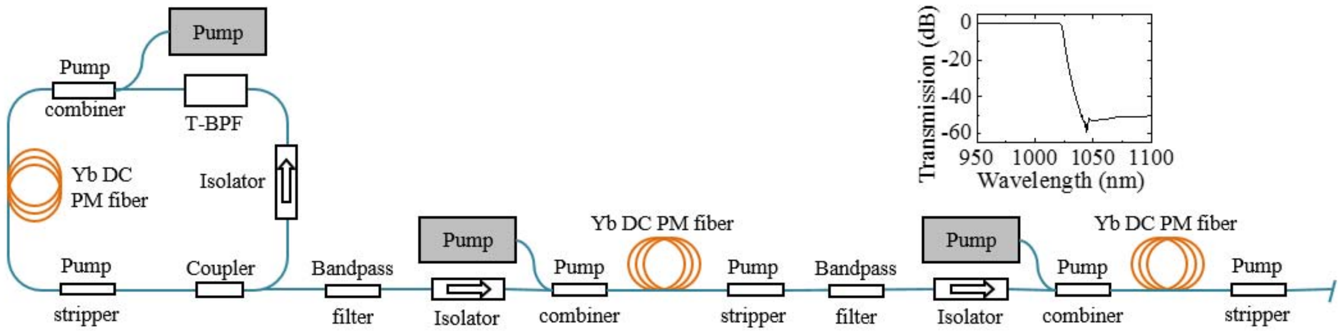

Fig. 1. A schematic diagram of the tunable fiber laser: the ring cavity master oscillator and two amplification stages. The inset at top right shows the bandpass filters' transmission spectrum. Both bandpass filters are removed when the system operates over 1020-1099 nm.

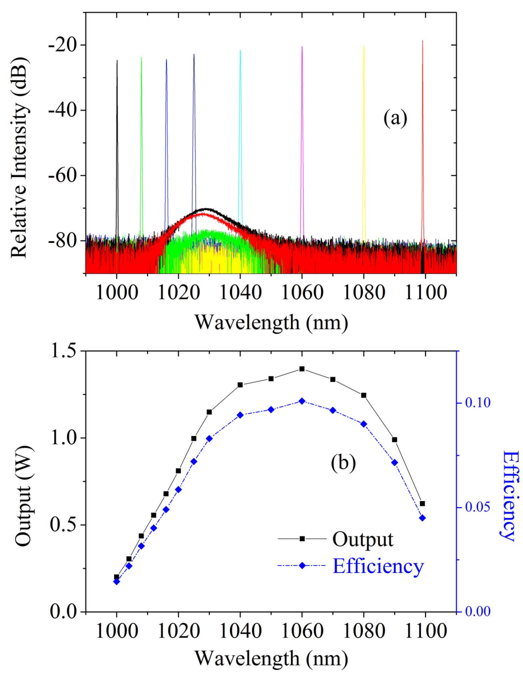

Fig. 2. (a) Spectra of the master oscillator at some different wavelengths (0.02 nm resolution of the spectrum analyzer). All the spectra in this letter are only comparable within each individual ones. (b) Output power and efficiency versus laser wavelength.

cleaved to avoid back reflection. The whole laser system is fiber-connected and polarization-maintaining.

III. Results and Discussion

A. Ring Cavity Master Oscillator

The wavelength tunable master oscillator lases over 1000-1099 nm, which is limited by the tuning range of the T-BPF. The Yb-doped fiber is chosen to be only 0.5 m long, which allows lasing even at 1000 nm. Fig. 2(a) shows the output spectra when the laser is tuned at different wavelengths. ASE is more than 60 dB lower than the laser, when the laser is tuned between 1016 nm and 1080 nm. At the edges of the tuning range, ASE is detected due to smaller emission cross section of Yb ion. ASE is highest when the laser is at 1000 nm, because of the strong re-absorption of Yb-doped fiber. However, the ASE is still 45 dB lower than the signal and less than 1 percent in output. The output power versus wavelength is shown in Fig. 2(b) with a fixed pump power of 13.8 W. The efficiency peaks at 1060 nm as expected, but only achieves 10.1 % due to the short gain fiber. For clear comparison, the output of master oscillator is set to 150 mW over the whole wavelength range in the following amplifier study. 150 mW is much higher than the saturation power of the Yb doped fiber over the tuning range except that close to 1099 nm. At this power level, the laser linewidth is about 0.2-0.3 nm.

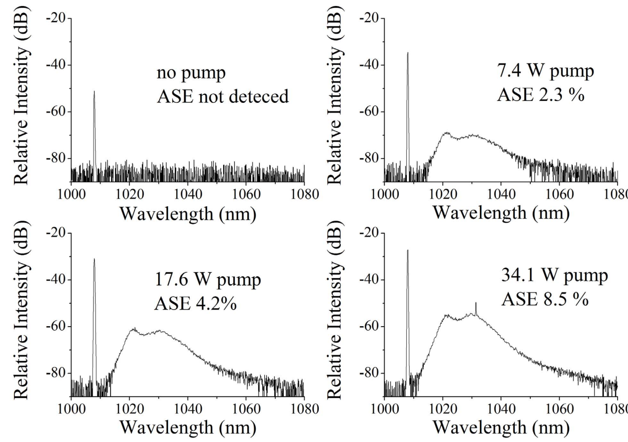

Fig. 3. Spectra of 1008 nm amplifier at different pump power.

B. 1st Stage Amplifier

We are mainly interested in the amplification in the range of 1000-1025 nm, which is limited by ASE and parasitic lasing at longer wavelength. For instance, Fig. 3 shows the spectra of the 1008 nm amplifier at different pump power. As the pump power increases, the ASE grows much faster than the signal and its fraction increases, ultimately parasitic oscillations at 1031 nm occurs. Thus ASE must be controlled for efficient amplification.

According to [15], the gain of signal is related to gain of ASE peak and pump absorption in Yb-doped silica fibers, by the emission and absorption cross sections, as well as the fiber geometry. To achieve higher gain at short wavelength with ASE under control, fiber with a smaller clad-to-core area

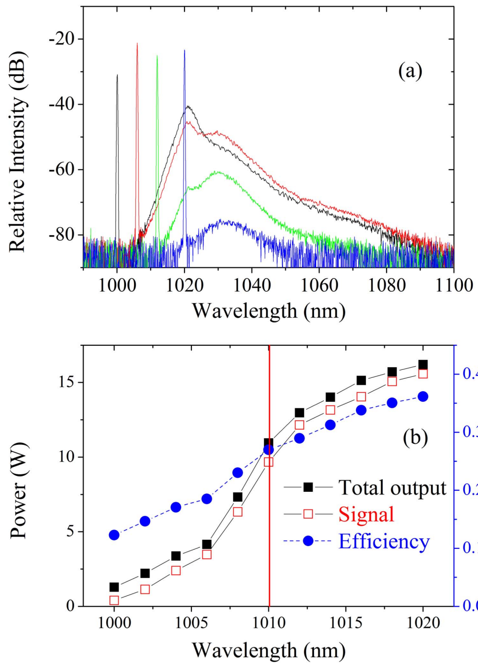

Fig. 4. (a) Output spectra of the 1st stage amplifier from 1000 to 1020 nm. (b) The total output power, signal power and efficiency as functions of the wavelength. At wavelength shorter than 1010 nm, the power is limited by parasitic oscillation.

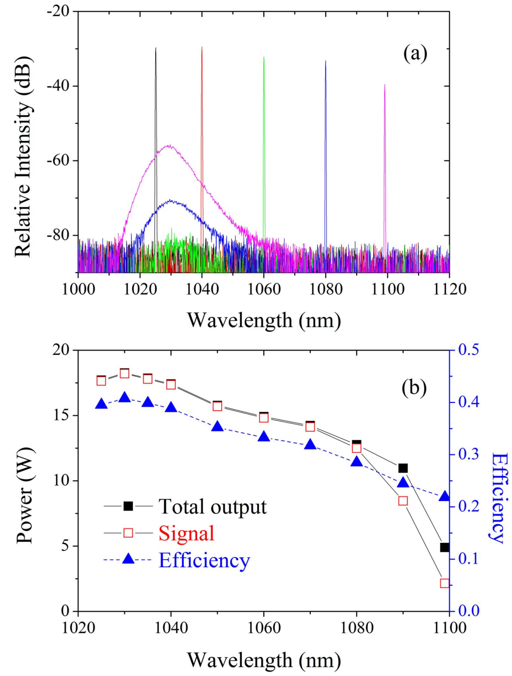

Fig. 5. (a) Output spectra of the 1st stage amplifier from 1025 to 1099 nm. (b) The dependence of the maximum total output, signal power, and efficiency on laser wavelength.

ratio is found to be favorable, and lower pump absorption would be another way by decreasing the difference between the gain of the signal and ASE [16]. Therefore, Yb-doped fiber with a core diameter of 10 μm and a numerical aperture of 0.075, whose clad-to-core ratio is smallest among the commercial double-cladding single mode fibers at 1 μm, is chosen, and only ~1 m fiber is used in this stage in priority of ASE control instead of efficiency. Furthermore, the fiber-pigtailed bandpass filter is inserted after the seed for amplification of 1000-1020 nm, to reduce the ASE at especially ~ 1030 nm.

Fig. 4(a) shows output spectra of amplifiers from 1000 to 1020 nm at the highest output. As the laser wavelength is shorter, ASE becomes more significant and the spectrum changes gradually from a single peak at ~1030 nm to twin peaks, then to a single peak at ~ 1020 nm, because of residual ASE at 1020 nm in the seed. Fig. 4(b) shows the amplifier output power and efficiency at different wavelength. As the wavelength becomes shorter, the amplifier power and efficiency decrease, due to smaller emission cross section and higher absorption at signal wavelength. When the laser wavelength is shorter than 1010 nm, the amplifier output is limited by parasitic oscillation.

It is interesting to know at what level of ASE gain parasitic oscillation takes place. The gain can be calculated by comparing the spectrum of input seed laser and the amplifier. It is found that when the amplifier starts to see parasitic oscillation, the gain of the amplifier at 1021 and 1030 nm are approximately 45 and 55 dB, respectively.

For the range of 1020-1099 nm, the fiber-pigtailed bandpass filter is removed since it blocks the seed laser. Fig. 5(a) shows the spectra at highest output power of representative wavelengths. Because the amplifier is designed for shorter wavelengths, ASE is detected as the laser wavelength is longer than 1060 nm. It increases quickly due to smaller emission cross section at longer wavelength. However, the fraction of ASE in the output is negligible until 1080 nm. At the far end of the tuning range, amplification at 1099 nm is limited by parasitic oscillation.

To summarize, after 1st stage amplifier, >8 W output over 1010-1020 nm (with ASE filter) and 1020-1090 nm (without filter) is achieved with maximum 18.2 W at 1030 nm and ASE less than 4 %. The efficiency is in positive correlation with the emission cross section as expected. At the edge of the tuning range, ASE is much more severe, so that parasitic oscillation occurs. Nevertheless, at 1002 nm and 1099 nm the output power is still >1 W. According to the spectra measured with 0.02 nm resolution, the laser linewidth is not noticeably broadened after amplification.

C. 2nd Stage Amplifier

To further increase the output power, another amplifier stage is added, whose design remains the same except longer gain fiber considering the larger seeding power. The bandpass filters are also used when the system works at wavelength shorter than 1020 nm. The seeding power is limited to 5 W for the safety of the isolator and bandpass filter, except at wavelengths over 1000-1008 nm and 1099 nm where such power can't be provided.

As the laser wavelength gets shorter, because ASE in the 1st stage amplifier output couldn't be entirely removed by the bandpass filter, the 2nd stage amplification at short wavelength becomes more difficult, even impossible. When the amplifier is injected with 1.02 W of 1002 nm laser only, which

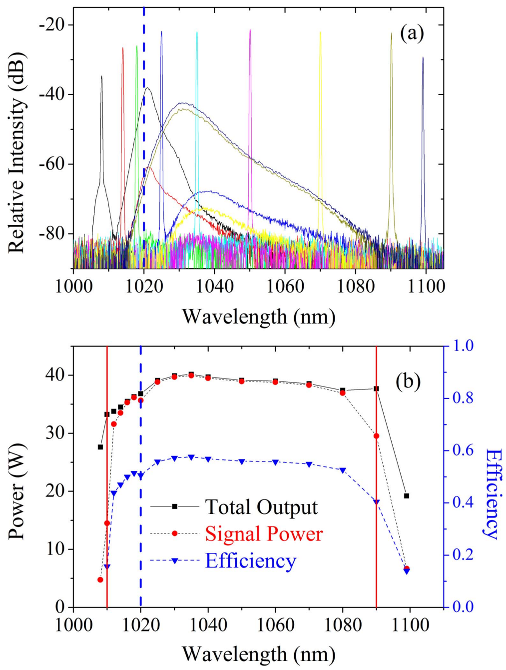

Fig. 6. (a) The direct output spectra of the 2^{nd} stage amplifier at wavelengths over 1008-1099 nm. (b) The total output, laser output and efficiency as functions of the wavelength for the second stage amplifier. The output power between the two red lines are limited by pump power, while the others are limited by parasitic oscillation. When the system operated on the left side of the blue vertical dash lines in (a) and (b), the bandpass filters were inserted in the system for ASE suppression, while on the right side, they were removed.

contains ASE of 27 %, and without pump, parasitic oscillation at 1020 nm occurs already. As wavelength is longer, parasitic oscillation threshold becomes higher. However, the ASE is so severe that the laser isn't amplified at all until 1008 nm. With 4.85 W 1008 nm input and 41.9 W pump power, the ratio of ASE in the total output exceeds 85% and the calculated signal power is less than the input.

At longer laser wavelength, because of less residual ASE in the input from 1^{st} stage amplifier and smaller ASE gain, the ASE decreases and becomes negligible as Fig. 6(a) shows. At first sight, it looks abnormal that ASE is seen in the spectrum of 1025 nm amplifier while no ASE is detected for the 1018 nm amplifier. The reason is that the 1018 nm input has higher SNR due to the bandpass filter, which was removed as the laser wavelength became longer than 1020 nm. Though ASE is buried in the noise in the 1025 nm seed from the 1st amplifier as Fig. 5(a) shows, it contains more ASE compared with the 1018 nm input whose ASE was weakened by the bandpass filter. A seed laser with high SNR is critical for amplification at the wings of gain spectrum.

When the laser wavelength increases further, ASE re-emerges but remains negligible until 1090 nm as shown in Fig. 6(a). Nevertheless, parasitic oscillation at 1030 nm becomes the restriction of amplification at 1099 nm. Up to 6.68 W at 1099 nm is obtained with an efficiency of 14% only, because the ASE extracts the stored energy much more efficiently. Compared with the 1st stage amplifier, the higher input power helps in controlling ASE.

Fig. 6(b) summarizes the total output, laser output and the efficiency as functions of the laser wavelength for the 2^{nd} stage amplifier from 1008 to 1099 nm. A maximum power of 40 W is achieved at 1035 nm and a minimum of ~10 W is obtained at the tuning edge for a maximum pumping power of 60.6 W.

IV. Conclusion

We have demonstrated a wavelength widely tunable, single mode Yb-doped all-fiber MOPA system with commercial double clad PM fiber. By properly designing the system and inserting ASE filters when the laser wavelength is shorter than 1020 nm, the ASE is diminished and the tuning range extends to shorter wavelength. By single stage amplification, the tuning range of 1002-1020 nm is covered with multi watt output, while >8 W over 1010-1090 nm is achieved with a maximum power of 18.2 W at 1030 nm. With a second amplifier, >30 W over the range of 1014-1080 nm with ASE less than 1% and efficiency of ~50 %, is demonstrated. At wavelength as short as 1010 nm, the output is still as high as 14.5 W. The laser system is built with off-the-shelf components and all-fiber-connected. The laser is being used for laser cooling of Yb-doped solids with wavelength tuning from 1010 to 1030 nm.

References

[1] R. Royon, J. Lhermite, L. Sarger, and E. Cormier, "High power, continuous-wave ytterbium-doped fiber laser tunable from 976 to 1120 nm," *Opt. Exp.*, vol. 21, no. 11, pp. 13818–13823, 2013.

[2] H. M. Pask *et al.*, "Ytterbium-doped silica fiber lasers: Versatile sources for the 1–1.2 μm region," *IEEE J. Sel. Topics Quantum Electron.*, vol. 1, no. 1, pp. 2–13, Apr. 1995.

[3] M. Auerbach *et al.*, "10 W widely tunable narrow linewidth double-clad fiber ring laser," *Opt. Exp.*, vol. 10, no. 2, pp. 139–144, 2002.

[4] M. Hildebrandt, M. Frede, and D. Kracht, "Narrow-linewidth ytterbium-doped fiber amplifier system with 45 nm tuning range and 133 W of output power," *Opt. Lett.*, vol. 32, no. 16, pp. 2345–2347, 2007.

[5] A. Silva, K.-J. Boller, and I. D. Lindsay, "Wavelength-swept Yb-fiber master-oscillator-power-amplifier with 70 nm rapid tuning range," *Opt. Exp.*, vol. 19, no. 11, pp. 10511–10517, 2011.

[6] P. Zeil and F. Laurell, "On the tunability of a narrow-linewidth Yb-fiber laser from three- to four-level lasing behaviour," *Opt. Exp.*, vol. 19, no. 15, pp. 13940–13948, 2011.

[7] M. Sheik-Bahae and R. I. Epstein, "Optical refrigeration," *Nature Photon.*, vol. 1, no. 12, pp. 693–699, 2007.

[8] D. V. Seletskiy, S. D. Melgaard, S. Bigotta, A. Di Lieto, M. Tonelli, and M. Sheik-Bahae, "Laser cooling of solids to cryogenic temperatures," *Nature Photon.*, vol. 4, no. 3, pp. 161–164, 2010.

[9] B. Zhong, J. Yin, Y. Jia, L. Chen, Y. Hang, and J. Yin, "Laser cooling of Yb^{3+}-doped $LuLiF_4$ crystal," *Opt. Lett.*, vol. 39, no. 9, pp. 2747–2750, 2014.

[10] S. G. Porsev and A. Derevianko, "Hyperfine quenching of the metastable $^3P_{0,2}$ states in divalent atoms," *Phys. Rev. A*, vol. 69, no. 4, p. 042506, 2004.

[11] H. Hachisu *et al.*, "Trapping of neutral mercury atoms and prospects for optical lattice clocks," *Phys. Rev. Lett.*, vol. 100, no. 5, p. 053001, 2008.

[12] H. Xiao, P. Zhou, X. L. Wang, X. J. Xu, and Z. J. Liu, "High power 1018 nm ytterbium doped fiber laser with an output power of 309 W," *Laser Phys. Lett.*, vol. 10, no. 6, p. 065102, 2013.

[13] F. Beier *et al.*, "1009 nm continuous-wave ytterbium-doped fiber amplifier emitting 146 W," *Opt. Lett.*, vol. 39, no. 13, pp. 3725–3727, 2014.

[14] D. V. Seletskiy, S. D. Melgaard, R. I. Epstein, A. Di Lieto, M. Tonelli, and M. Sheik-Bahae, "Precise determination of minimum achievable temperature for solid-state optical refrigeration," *J. Lumin.*, vol. 133, pp. 5–9, Jan. 2013.

[15] J. Nilsson, J. D. Minelly, R. Paschotta, A. C. Tropper, and D. C. Hanna, "Ring-doped cladding-pumped single-mode three-level fiber laser," *Opt. Lett.*, vol. 23, no. 5, pp. 355–357, 1998.

[16] J. Hu, L. Zhang, H. Liu, K. Liu, Z. Xu, and Y. Feng, "High-power single-frequency 1014.8 nm Yb-doped fiber amplifier working at room temperature," *Appl. Opt.*, vol. 53, no. 22, pp. 4972–4977, 2014.