Erbium:ytterbium co-doped large-core fiber laser with 297 W continuous-wave output power

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Abstract

We have demonstrated a high-power and high-efficiency erbium:ytterbium (Er:Yb) co-doped fiber laser that produces 297 W of continuous-wave output at 1567 nm. The slope efficiency with respect to the launched pump power changed from 40% to 19% at higher output power due to the onset of Yb co-lasing at 1067 nm. However, the Yb co-lasing was essential for the suppression of catastrophic pulsation at high pump powers that otherwise results if the Yb-band gain is allowed to build up. Spectroscopic characteristics of the fiber and the impact of the Yb co-lasing on the 1567 nm slope efficiency are also discussed.

Index terms: Erbium, Ytterbium, Lasers, Optical fiber lasers, Optical fiber amplifiers

I. Introduction

Several advantages of the 1.5 – 1.6 μm wavelength range including its relatively "eye-safe" nature, good atmospheric transmission, and low fiber loss make high-power fiber lasers in this wavelength range of great importance in many scientific and engineering applications, such as free-space communication, range finding, and LIDAR [1]. Furthermore this wavelength range also facilitates the use of widely available low-cost, mature and reliable, telecom components, such as isolators, couplers, tunable sources, fast modulators and detectors that enable precise high-speed control of signals [2]-[5]. For high-power cladding-pumping, erbium:ytterbium (Er:Yb) co-doped fibers (EYDFs) are investigated extensively because of their excellent power scalability combined with readily available high-power pump diodes at 915 – 980 nm [5]-[13]. EYDFs rely on indirect pumping of the lasing Er ions through nonradiative energy transfer from the Yb ions [6], [7]. This Yb co-doping improves the pump absorption which is necessary for power-scaling through cladding-pumping. However, EYDFs are significantly less efficient than Yb-doped ones emitting at 1.1 μm [14]. This is due mainly to the relatively large quantum defect and some problematic issues related to the fiber as well as the laser or amplifier configuration. These issues that can degrade the efficiency and hamper power-scaling of EYDFs include inefficient energy transfer between Yb and Er ions [15], excessive thermal load [11], and spurious Yb emission at 1 – 1.1 μm [5], [10]. In contrast to the situation for Yb-doped fiber lasers, EYDFs have failed at significantly less pump powers than have been available in experiments [5], [11] and thus the fibers and the configurations rather than the available pump power have limited the output power. Up to date, the record output power from EYDF lasers and amplifiers with single-ended output has remained below 160 W [5], [13]. To meet the increasingly demanding needs of different applications, optimization of the fiber gain medium and the device configuration is crucial for controlling unwanted emission from excited Yb ions, for improving the efficiency, and for further power-scaling of devices that make full use of the power available from diode pump sources.

In this paper we present a record power from any EYDF. We used a single-stage laser configuration which was able to generate 297 W of output power at 1567 nm. The output power was not limited by the fiber itself but the available pump power. However, the laser efficiency was reduced by the onset of Yb co-lasing at ~ 1060 nm with a comparable amount of output power at the maximum pump power. It was found that a controlled Yb co-lasing was particularly essential for our case in order to suppress the catastrophic pulsation of Yb emission at high pump powers. Further details will be discussed later on. We also discuss the fluorescence decay characteristics of the dopant ions in the fiber used in the experiments. Fluorescence decay measurements show that there are a fraction of Yb ions that are isolated from the Er ions. These ions can generate considerable Yb-band gain already at low pump powers. In the absence of feedback in the Yb gain band, the Yb-band gain will soon build up to values where strong spurious emission occurs as pump energy is absorbed in the isolated Yb ions. This can lead to self-pulsation and damage of the fiber. With a cavity the energy that builds up in the isolated Yb ions is drained out in a stable way through moderate lasing already at gain levels that are sufficiently low to avoid the initiation of self-pulsation.

II. Experimental Results and Discussion

Figure 1 shows a schematic of the laser system. We use a diode-stack-based laser to cladding-pump the fiber. It can emit up to 1.2 kW at a center wavelength of ~ 975 nm at maximum driving current. The fiber used in the experiment was fabricated by SPI Lasers. The inner cladding is 600 μm in diameter and D-shaped to improve the pump absorption characteristics. The outer low-refractive-index polymer coating provides a nominal inner-cladding numerical aperture (NA) of 0.48. The core is made of phosphosilicate co-doped with Er and Yb ions by the solution doping technique [6], [7]. The core has a large diameter of 30 μm and an NA of 0.21. This leads to a calculated V-parameter of 12.6 and a calculated effective area for the fundamental mode of 393 μm^2 at 1567 nm. The absorption for light in the inner cladding from the Er and Yb ions are 0.11 dB/m at 1535 nm and 3.8 dB/m at 976 nm. The EYDF used for the laser is 6 m long and both ends are cleaved perpendicularly to the fiber axis. The focal length and NA of the focusing lens are 25 mm and 0.45, respectively. The pump launch efficiency is ~ 85% relative to the power incident onto the fiber. Essentially all, or ~ 99%, of the launched pump power is absorbed in the fiber. The laser cavity is formed between the bare fiber facet at the pump launch end of the fiber and a dichroic mirror butt-coupled to the fiber at the rear end. The dichroic mirror has high reflection at 1.5 – 1.6 μm and high transmission for the pump and Yb emission wavelengths at ~ 1 μm. Butt-coupling enables a relatively compact and simple, and more stable, configuration in comparison with the lens-coupling employed in our previous experiments [10], [11]. It is noteworthy that the butt-coupled mirror can be replaced by a thin dielectric coating that is directly deposited onto the fiber facet or, alternately, a fiber Bragg grating that is directly written in the EYDF or in a separate fiber spliced to it. To steer the output beam from the pump beam path, a dichroic mirror of high reflection at 1.5 – 1.6 μm and of high transmission at 0.9 – 1.1 μm is positioned between the fiber and the pump diode. Another dichroic mirror of high reflection at ~ 1060 nm and of high transmission at ~ 975 nm is also inserted in the pump beam path to separate out any lasing component at ~ 1060 nm that may arise at the high Yb excitation levels that can result at high pump powers. Both ends of the fiber are held in temperature-controlled metallic V-grooves that are designed to prevent thermal damage to the fiber. The remainder of the fiber is air fan-cooled. Thermal damage is an important issue with EYDFs, without as well as with Yb co-lasing, because of the quantum defect heating and the comparatively low efficiency. In the past, EYDFs have over-heated at high pump powers [11]. Lower pump absorption would help in this respect, by reducing the heat deposition per unit length. However, highly efficient EYDFs require high Yb concentrations, and even then, the 1.6 μm power that can be generated per unit volume of gain medium is limited. We have therefore designed the fiber with a large core of standard composition for EYDFs, and with a large inner cladding that reduces the pump absorption and increases the surface area for heat dissipation. The large inner cladding naturally lends itself to pumping with high-power multimode diode sources.

Figure 2(a) shows the laser's power performance at 1.6 μm. 297 W of maximum output power was achieved from the EYDF and this was limited by the available pump power. The laser output was centered at a wavelength of 1567 nm at the maximum output power as shown in Fig. 2(b). The slope efficiency of the laser with respect to the launched pump power was 40% at low pump power and dropped down to 19% at high pump power because of bottle-necking in the Yb → Er energy transfer. Owing to increasing Yb excitation at high pump powers, there was also an onset of Yb co-lasing. Figure 3(a) shows the power characteristics of the Yb co-lasing. The threshold was ~ 210 W of launched pump power and the output power in the forward and backward directions was 338 W in total at the maximum pump power. At high powers, the lasing wavelength was centered at 1067 nm as shown in Fig. 3(b), while it was shorter at lower powers. The short-term temporal power characteristics in terms of standard deviations were < 1.3% for Er (~ 1.6 μm) emission and < 1.1 % for Yb (~ 1.1 μm) emission at the maximum pump power, measured with a 5 GHz photo-detector and a 400 MHz bandwidth oscilloscope. Although we did not perform a long-term stability test for the laser system, there was no sign of significant power degradation during the course of the experiments with daily operation.

Since both fiber ends had normal flat cleaves, there was a laser cavity for Yb emission as well as for Er emission. One might think that configurations with, for example, a band-rejection filter for Yb emission inside the cavity [12] or angle-cleaved fiber ends combined with external feedback mirrors reflecting only at ~ 1.6 μm would help in reducing spurious Yb emission. However this is only correct to a limited degree. In practice, as the pump power increases, the excitation of Yb ions and the Yb-band gain is likely to soon build up to levels where high-power Yb-band ASE (Amplified Spontaneous Emission) results even with such point-wise filtering or suppression of feedback [5]. Note that insofar as spectroscopic parameters remain constant, a higher Yb excitation level is necessary when the pump power and the 1.6 μm output power increase. Thus, in the absence of a distributed filter that suppresses Yb-band ASE throughout the fiber, it is a potential concern even in the best of Er:Yb co-doped gain media, although a better Yb → Er energy transfer increases the 1.6 μm output power that can be obtained. Furthermore the slope efficiency of the Yb ASE in the absence of a cavity can be comparable to that of Yb lasing in the presence of a cavity [5]. For example, in Ref. [5] the single-sided Yb ASE slope efficiency reaches ~ 30% in the high-power regime. Thus, we might expect that the introduction of a Yb-band cavity, as was employed in Ref. [10], need not significantly degrade the efficiency of the Er emission. At the same time, the cavity will prevent a high Yb-band gain to build up. Such a high gain can otherwise lead to the generation of high-energy pulses that can damage the laser.

Our current experiments further verified this. A configuration with an angle-cleaved rear fiber end, together with a lens-coupled dichroic reflector, was used to suppress the 1.1 μm feedback in that end of the fiber. However this configuration did not work well at high powers. While the elimination of the cavity helps in reducing the Yb emission somewhat, it also leads to instabilities and fiber failure. We observed that unstable Yb emission including lasing due to excessive gain and spurious feedback in the Yb-band consistently led to catastrophic failure of the fiber facets at an Er output power level of 120 − 150 W. This Er power level is only slightly above that obtained at the threshold for lasing in the presence of the cavity, and is even below the point at which the Er power rolls over in the presence of the cavity (see Fig. 2). Thus, we switched to a modified configuration with a butt-coupled mirror according to Fig. 1, which eventually worked well. This created a modest ~ 5% feedback at around 1.1 μm, dominated by the feedback from the fiber facet, The feedback included a contribution from a residual mirror reflectivity, which may also have led to some etalon effects in the feedback spectrum. This feedback together with the ~ 4% Fresnel feedback from pump launch end formed the laser cavity for the Yb emission. The laser cavity stabilized the 1.1 μm emission, so that fiber failure could be avoided at high pump powers. Thus, our strategy of controlled 1.1 μm co-lasing finally allowed us to reach a stable output power of 297 W at 1.6 μm. We would like to emphasize that this Yb co-lasing configuration led to a gain-clamping or gain-limiting effect for the excited Yb ions [16], [17], which eliminated gigantic pulsation of the emission from the Yb ions. This enabled us to use the full power of our diode pump source. Furthermore, there was no noticeable difference in the efficiency of the Er emission with and without an Yb-band cavity although it ended up with roll-over at high pump powers (> 450 W).

More careful experiments with varying Yb co-lasing power (e.g., with varying Yb-band feedback), is needed to fully explore the relation between the Yb co-lasing and the Er efficiency. However, such a study is not straightforward at high power levels. More precise alignment-free all-fiber cavities that can be implemented at lower power levels with small-core EYDFs are probably better suited to such investigations, and may well allow for improved Er slope efficiencies with optimized cavities that at the same time prevent Yb-band pulsing. Still, insofar as it is possible, the best approach to suppress damaging Yb emission and at the same time improve the efficiency of the Er emission would be to improve the energy transfer from Yb to Er ions. Ideally, we would like the energy transfer to be fast and complete, so that the Yb excitation remains below the level where there is a net gain in the Yb-band for all pump powers of interest. The spectroscopy and energy transfer characteristics of EYDFs have been analyzed in the past [18]-[22]. The characteristics vary from fiber to fiber. To analyze the energy-transfer characteristics of the EYDF we used here, we measured the fluorescence decay of Yb and Er ions in a short piece of fiber, excited by a 920-nm Q-switched neodymium-doped fiber laser [23]. The fluorescence signal is proportional to the number of excited ions in the fiber. Figure 4 shows Yb fluorescence decay curves of our EYDF. The decay curves are invariably strongly non-exponential, with a fast initial decay followed by a much slower decay. The fast initial decay corresponds to a rapid de-excitation of the Yb ions (donors), as these donor ions transfer their energy to nearby ground-state Er ions (acceptors). Note here that the fibers were excited at low repetition rates with different pulse energies, down to values so low that effects such as saturation of acceptors (i.e., non-negligible excitation of Er ions) could be avoided. However, EYDFs also contain Yb ions that are isolated from the Er ions, and therefore unable to nonradiatively transfer energy to them. These give rise to the slower-decaying tail of the fluorescence, with decay rates that approach the purely radiative decay rate of approximately $(1.3\ \text{ms})^{-1}$ in Yb:phosphosilicate [20]. From Fig. 4, we see that between 50% and 70% of the Yb ions relax within 10 μs. Roughly a fraction 95% (i.e., $1 - e^{-3}$) of the ions decay with a time constant of 10 – 15 μs. The remaining ions decay at a slower rate. Roughly 2% of the ions relax with a time constant of 100 μs or slower. Although there is a gradual transition from isolated slow-decaying to coupled fast-decaying Yb ions, it seems reasonable to consider that between 2% and 5% of the Yb ions are isolated. It is noteworthy that this fraction is considerably lower than in most EYDFs we have characterized, and this is presumably one explanation for the excellent power scalability that we report in this paper. Still, even this level of isolated ions can be expected to affect the laser characteristics.

As already noted, the indirect pumping of the Er ions implies that a higher Yb excitation level is needed for a higher Yb $\rightarrow$ Er energy transfer rate, when the pump power increases. In most models, the rate at which Er ions in the ground state ($^4I_{15/2}$) are excited to the upper laser level ($^4I_{13/2}$) is proportional to the Yb excitation level [18]-[22]. This seems reasonable, but it does suggest that the laser emission from the Er ions cannot increase once the Yb excitation level reaches its maximum level throughout the fiber. Such complete saturation has been observed in EYDFs with poor energy transfer characteristics [15]. However, the Er output power normally continues to grow even after the onset of Yb co-lasing [24]. It is very hard to explain this feature in a simple way; however, we think that a couple of factors, such as thermal effects on Yb $\rightarrow$ Er energy transfer rate and non-uniform Yb and Er ion distribution are closely linked to it. In the high power regime, thermal effects are important [11]. The Yb ground-state absorption at the co-lasing wavelength increases with temperature because of a higher thermal population of higher Stark levels. As a result, the Yb excitation can increase with pump power even under co-lasing conditions when thermal effects are significant. In addition, when there are two different kinds of Yb ions in the fiber, i.e., isolated ions and coupled ions, the Er output power can continue to grow after the co-lasing threshold even with or without the thermal effects. That it, at the threshold for Yb co-lasing, a large fraction of the excited Yb ions are isolated ions, since their relatively long upper level lifetime (up to 1.3 ms [20]) makes them easy to excite. The excitation level of the coupled Yb ions that is crucial for the Yb $\rightarrow$ Er energy transfer is still lower than that required for lasing. Thus, it can keep increasing with higher pump power, up to the laser threshold level. At the same time the excitation level of the isolated Yb ions decreases to keep the total Yb excitation level clamped to the laser threshold value. Furthermore, depending on the precise parameter values, the emission from the isolated Yb ions can even be absorbed by the coupled Yb ions if their excitation level is sufficiently low. For example, it is well known that 1064 nm lasers can be used for pumping of EYDFs [18], [28]. This would provide a radiative coupling between (nonradiatively) isolated Yb ions and coupled Yb ions, and so would indirectly provide some coupling between isolated Yb ions and Er ions. In this regime the Yb co-lasing could contribute to Er lasing. However, as the excitation level of coupled Yb ions increases for higher pump powers, also these will eventually start to amplify the radiation field at ~ 1060 nm. When significant power is funneled to the radiation field rather than to the Er ions, the output power at ~ 1.6 μm would be expected to suffer, but not necessarily before. That is, the drop in the Er slope efficiency does not necessarily happen at the Yb co-lasing threshold.

Figure 2(a) shows that the Er output power kept increasing without a significant drop in the slope efficiency up to ~ 450 W of launched pump power, which is beyond the Yb co-lasing threshold of ~ 210 W of launched pump power. Based on our hypothesis stated above, the Yb output power for pump powers between 210 and 450 W should be due mainly to excited isolated ions. We estimate that only 1.6% of the coupled Yb ions, as averaged throughout the fiber, are excited at a pump power of 210 W while the total excitation level that is required for Yb lasing is 3.6%, based on room-temperature absorption and emission cross-section spectra. We have assumed here that 40% of the Er ions are excited when lasing and this leads to an increase of the Yb $\rightarrow$ Er energy transfer time from 10 μs (see Fig. 4) to 16.6 μs. Since the 1.6% excitation level is still lower that the upper limit of the total excitation rate of 3.6%, the excitation level of the coupled Yb ions can keep increasing. The 1.6% excitation level is close to that required for net gain at 1067 nm (estimated to 1.4%), so the Er slope efficiency would not be expected to drop at the onset of co-lasing, in agreement with experiments. The shorter Yb emission wavelength at the onset of Yb co-lasing further increases the Yb excitation level required for net gain, as does a non-negligible temperature, and it is possible that the emission from isolated Yb ions did make a small contribution to the pumping of the Er ions near the Yb co-lasing threshold.

Our estimates suggest that the coupled Yb ions would reach lasing at ~ 480 W of launched pump power even in the absence of isolated Yb ions. Thus, one might think that beyond this point, the Er output power would not grow much for higher pump powers. However, this is also at odds with the experiments. Uncertainty in parameter values is certainly one possible explanation for the discrepancy. There is also a spatial equalization of the Yb excitation between different parts of the fiber when the pump power increases. This allows the Er output power to grow even when the average Yb excitation level is clamped. However we believe that a possible key explanation for this continuous increase of the Er output power seen with our fiber is the thermal effect on the spectroscopy of the Er and Yb ions [24]-[28]. Simulation results in Ref. [14] showed no clamping of the Er output power, even high above the co-lasing threshold. This was due to the increased ground state absorption at high temperatures. The influence of the temperature on the laser performance in the presence of isolated ions and coupled ions and their different saturation powers was however not discussed. Nevertheless, at least in some regime, an increase in temperature has a positive effect on EYDFs [24], [26], [28]. High core temperatures, e.g., above 100ºC, are readily reached in a high-power EYDF because of the relatively large quantum defect and low conversion efficiency, as seen in Ref. [11].

The Yb co-lasing is further complicated by the spatial properties of the laser beams. The beam quality factor (M^2) was measured to 3.9 for the Er emission. Thus, given the large core dimension and a relatively high core NA of 0.21 (V = 12.6 at 1567 nm), the beam quality was quite good. For the Yb emission, the beam quality factor was 12. One of the reasons for the worse beam quality for the Yb emission is that in principle the core supports more modes at 1067 nm (V = 18.5 at 1067 nm). A further complication is that different modes see different effective concentrations and excitation levels of isolated and coupled Yb ions. For example, if the 1567 nm field is unable to efficiently extract power from the edge of the core since the Er emission field that lases in lower-order modes basically has better overlap with the central part of the core, this can cause a build-up of the higher excitation of Yb ions in the edge region. Thus the 1067 nm radiation is expected to see a higher gain on the edge of the core, thereby leading to lasing in higher-order modes with worse beam quality [29]. Non-uniformity in Er and Yb ion concentration and couplings across the core can also partially be attributed to such beam quality discrepancy between Er and Yb emissions. Coiling to produce high bend losses for high-order modes [14] did not work well in this fiber because of the high NA of the core and the thick outer diameter of the fiber. Reducing the effective core NA by lowering the core index [14] or by raising the inner-cladding index through a raised-index pedestal region around the core [30] should help to improve the beam quality. Large low NA cores can even result in diffraction-limited beam quality as demonstrated in Ref. [14]. There, a nearly diffraction limited beam was readily achieved with a 40 μm core diameter with an NA of ~ 0.05.

III. Conclusion

We have demonstrated a high-power laser emitting in the eye-safe wavelength range. The laser is based on an EYDF capable of producing high-stability continuous-wave output at a record power level of 300 W and a wavelength of 1567 nm. At the same time, the laser produced a comparable output power at 1067 nm, resulting from emission from Yb ions. The overall optical-to-optical conversion efficiency of the laser system including both Er emission at 1567 nm and Yb emission at 1067 nm was 63% and the combined quantum slope efficiency was 85%. The 1567 nm slope efficiency was 40% at low powers and 19% at high powers. While there is room for improvements in the spectroscopy of the fiber in order to enhance the Yb $\rightarrow$ Er energy transfer, we found that the fraction of isolated ions in the fiber was considerably lower than in most EYDFs we had characterized [5], [10], [11], and this eventually led to the excellent power scalability. While the Yb co-lasing degraded the overall Er laser efficiency at high powers, the control of the Yb co-lasing with a laser cavity in the Yb gain band eliminated catastrophic pulsation at high pump powers through clamping of the maximum Yb-band gain.

The output power characteristics of the 1567 nm lasing and the 1067 nm co-lasing show several complex features. These can be attributed to inhomogeneity in Er and Yb ion couplings and thermal effects. We could see that the Yb excitation level and therefore the Er output power grows even after Yb co-lasing occurs and in the intermediate power range the Yb co-lasing does not significantly degrades the Er laser efficiency. Additional characterization combined with detailed numerical modeling including thermal effects on the spectroscopy and multimode propagation effects would be needed to better understand the complex characteristics of the Er and Yb laser emission in high-power EYDFs.

References

[1] V. Philippov, C. Codemard, Y. Jeong, C. Alegria, J. K. Sahu, J. Nilsson, and G. N. Pearson, "High-energy in-fiber pulse amplification for coherent lidar applications," Opt. Lett. vol. 29, no. 22, pp.2590-2592, 2004.

[2] B. C. Thomsen, Y. Jeong, C. Codemard, M. A. F. Roelens, P. Dupriez, J. K. Sahu, J. Nilsson, and D. J. Richardson, "60 W, 10 GHz 4.5 ps pulse source at 1.5 μm," CLEO 2004, San Francisco, May 16-21, 2004, paper CMAA4.

[3] D. Panasenko, P. Polynkin, A. Polynkin, J. V. Moloney, M. Mansuripur, and N. Peyghambarian, "Er-Yb femtosecond ring fiber oscillator with 1.1-W average power and GHz repetition rates," IEEE Photon. Technol. Lett., vol. 18, no. 7, pp. 853-855, 2006.

[4] M. D. Mermelstein, A. D. Yablon, and C. Headley, "Suppression of stimulated Brillouin scattering in an Er-Yb fiber amplifier utilizing temperature-segmentation," OAA 2005, Aug. 7-10, 2005, Budapest, Hungary, paper TuD3.

[5] Y. Jeong, J. K. Sahu, D. B. S. Soh, C. A. Codemard, and J. Nilsson, "High-power tunable single-frequency single-mode erbium:ytterbium codoped large-core fiber master-oscillator power amplifier source," Opt. Lett., vol. 30, pp. 2997-2999, 2005.

[6] J. D. Minelly, W. L. Barnes, R. I. Laming, P. R. Morkel, J. E. Townsend, S. G. Grubb, and D. N. Payne, "Diode-array pumping of Er^{3+}/Yb^{3+} co-doped fiber lasers and amplifiers," IEEE Photon. Technol. Lett., vol. 5, pp. 301-303, 1993.

[7] G. G. Vienne, J. E. Caplen, L. Dong, J. D. Minelly, J. Nilsson, and D. N. Payne "Fabrication and characterization of Yb^{3+}:Er^{3+} phosphosilicate fibers for lasers," J. Lightwave Technol., vol. 16, pp. 1990-2001, 1998.

[8] J. Nilsson, S.-U. Alam, J. A. Alvarez-Chavez, P. W. Turner, W. A. Clarkson, and A. B. Grudinin, "High-power and tunable operation of erbium-ytterbium co-doped cladding-

pumped fiber laser," IEEE J. Quantum Electron., vol. 39, no. 8, pp. 98-994, 2003.

[9] J. Nilsson, P. Scheer, and B. Jaskorzynska, "Modeling and optimization of short Yb^{3+}-sensitized Er^{3+}-doped fiber amplifiers," IEEE Photon. Technol. Lett., vol. 6, no. 3, pp. 383-385, 1994.

[10] J. K. Sahu, Y. Jeong, D. J. Richardson, and J. Nilsson, "103 W Erbium/ytterbium co-doped large-core fiber laser," Opt. Commun., vol. 227, pp.159-163, 2003.

[11] J. K. Sahu, Y. Jeong, D. J. Richardson, and J. Nilsson, "Highly efficient high-power erbium-ytterbium co-doped large core fiber laser," ASSP 2005, Vienna, Austria, 6-9 Feb., 2005, paper MB33.

[12] A. Yusim, J. Barsalou, D. Gapontsev, N. S. Platonov, O. Shkurikhin, V. P. Gapontsev, Y. A. Barannikov, and F. V. Shcherbina, "100 watt single-mode CW linearly polarized all-fiber format 1.56-µm laser with suppression of parasitic lasing effects," in Proc. SPIE, vol. 5709, Fiber Lasers II: Technology, Systems, and Applications, L. N. Durvasula, Andrew J. W. Brown, Johan Nilsson, Editors, April 2005, pp. 69-77.

[13] D. Y. Shen, J. K. Sahu, and W. A. Clarkson, "Highly efficient Er,Yb-doped fiber laser with 188W free-running and > 100W tunable output power," Opt. Express, vol. 13, no. 13, pp. 4916-4921, 2005.

[14] Y. Jeong, J. Sahu, D. Payne, and J. Nilsson, "Ytterbium-doped large-core fiber laser with 1.36 kW continuous-wave output power," Opt. Express, vol. 12, no. 25, pp. 6088-6092, 2004.

[15] P. K. Cheo and G. G. King, "Clad-pumped Yb:Er codoped fiber lasers," IEEE Photonics Technol. Lett., vol. 13, no. 3, pp. 188-200, 2001.

[16] M. Zirngibl, "Gain control in erbium-doped fiber amplifiers by an all-optical feedback loop," Electron. Lett., vol. 27, no. 7, pp. 560-561, 1991.

[17] S. Y. Kim, J. Chung, and B. Lee, "Dynamic performance of the all-optical gain-

controlled EDFA cascade in multiwavelength optical networks," Electron. Lett., vol. 33, no. 17, pp. 1475-1477, 1997.

[18] P. R. Morkel, "Modeling erbium/ytterbium-doped fiber amplifiers," in Proc. Optical Amplifiers and Their Applications Technical Digest, 1992, Washington, DC: Opt. Soc. Amer., 1992, vol. 17, pp. 206–209.

[19] E. Maurice, G. Monnom, B. Dussardier, and D. B. Ostrowsky, "Clustering effects on double energy transfer in heavily ytterbium–erbium-codoped silica fibers," J. Opt. Soc. Am. B, vol. 13, no. 4, pp. 693-701, 1996.

[20] M. Laroche, S. Girard, J. K. Sahu, W. A. Clarkson, and J. Nilsson, "Accurate efficiency calculation of energy transfer processes in phosphosilicate Er^{3+}-Yb^{3+} codoped fibers," J. Opt. Soc. Am. B, vol. 23, no. 2, 195-202, 2006.

[21] E. Yahel and A. Hardy, "Modeling high-power Er^{3+}-Yb^{3+} codoped fiber lasers," J. Lightwave Technol., vol. 21, no. 9, pp. 2044-2052, 2003.

[22] G. A. Sefler, W. D. Mack, G. C. Valley, and T. S. Rose, "Secondary energy transfer and nonparticipatory Yb^{3+} ions in Er^{3+}-Yb^{3+} high-power amplifier fibers," J. Opt. Soc. Am. B, vol. 21, no. 10, pp. 1740-1748, 2004.

[23] J. Kim, P. Dupriez, D. B. S. Soh, J. Nilsson, and J. K. Sahu, "Core area scaling of Nd:Al-doped silica depressed clad hollow optical fiber and Q-switched laser operation at 0.9 μm," Opt. Lett., vol. 31, no. 19, pp. 2833-2835, 2006.

[24] G. Canat, J.-C. Mollier, Y. Jaouën, and B. Dussardier, "Evidence of thermal effects in a high-power Er^{3+}–Yb^{3+} fiber laser," Opt. Lett., vol. 30, no. 22, pp. 3030-3032, 2005.

[25] D. I. Forsyth, S. A. Wade, T. Sun, X. Chen, and K. T. V. Grattan, "Dual temperature and strain measurement with the combined fluorescence lifetime and Bragg wavelength shift approach in doped optical fiber," Appl. Opt., vol. 41, no. 31, pp. 6585-6592, 2002.

[26] S. Baek, Y. Jeong, J. Nilsson, J. K. Sahu, and B. Lee, "Temperature-dependent

fluorescence characteristics of an ytterbium-sensitized erbium-doped silica fiber for sensor applications," Opt. Fiber Technol., vol. 12, no. 1, pp. 10-19, 2006.

[27] J. F. Philipps, T. Töpfer, H. Ebendorff-Heidepriem, D. Ehrt, R. Sauerbrey, "Spectroscopic and lasing properties of Er^{3+}:Yb^{3+}-doped fluoride phosphate glasses," Appl. Phys. B, vol. 72, pp. 399-405, 2001.

[28] C. J. da Silva, M. T. de Araujo, E. A. Gouveia, and A. S. Gouveia-Neto, "Fourfold output power enhancement and threshold reduction through thermal effects in an Er^{3+}/Yb^{3+}-codoped optical fiber laser excited at 1.064 μm," Opt. Lett., v. 24, pp. 1287-1289, 1999.

[29] H. Yoda, P. Polynkin, and M. Mansuripur, "Beam quality factor of higher order modes in a step-index fiber," J. Lightwave Technol., vol. 24, no. 3, pp. 1350-1355, 2006.

[30] P. Laperle, C. Paré, H. Zheng, A. Croteau, and Y. Taillon, "Yb-doped LMA triple-clad fiber laser," Photonics North 2006, Québec, Canada, Jun. 5-8, 2006, paper FB-07-3-3.

Figure and table captions

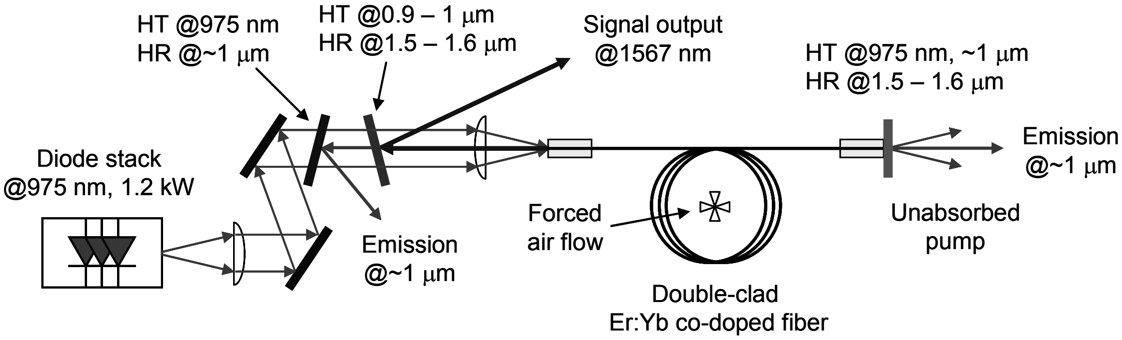
Fig. 1. Schematic of the Er:Yb codoped fiber laser system.

Fig. 2. (a) Output power at 1.6 μm vs. launched pump power. The saturation curve fit is based on $P_{laser} = P_{max}/(1 + P_{sat}/P_{pump})$, where P_{max} and P_{sat} are fitting parameters. (b) Output spectrum centered at 1567 nm.

Fig. 3. (a) Output power at 1.1 μm vs. launched pump power. (b) Output spectrum centered at 1067 nm.

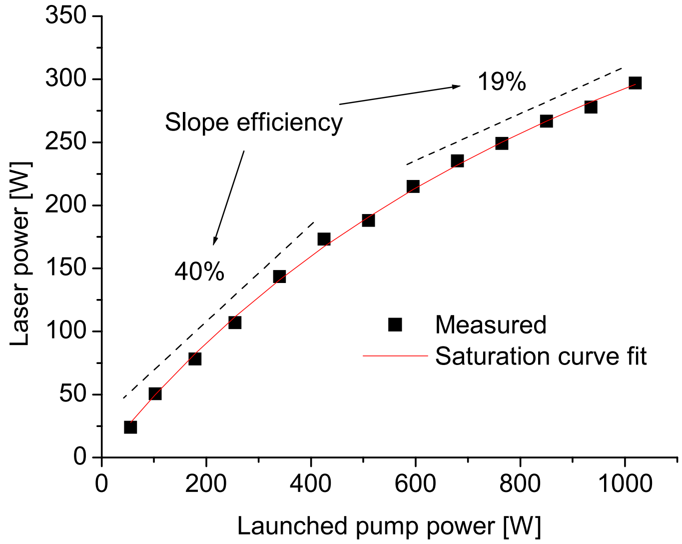
Fig. 4. Yb fluorescence decay curves at different excitation energies at ~ 920 nm with pulse duration of ~ 100 ns.

Fig. 1



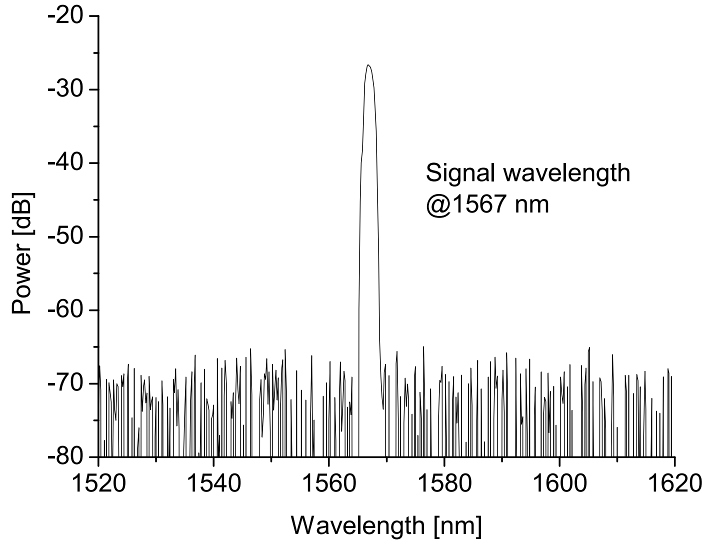
HT @975 nm
HR @~1 μm
HT @0.9 – 1 μm
HR @1.5 – 1.6 μm
Signal output
@1567 nm
HT @975 nm, ~1 μm
HR @1.5 – 1.6 μm
Diode stack
@975 nm, 1.2 kW
Emission
@~1 μm
Forced
air flow
Emission
@~1 μm
Unabsorbed
pump
Double-clad
Er:Yb co-doped fiber

Fig. 2(a)



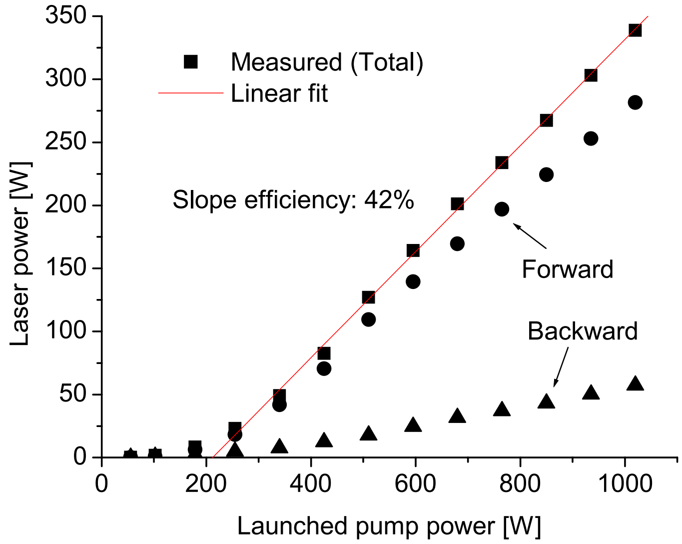
350
300
250
200
150
100
50
0
Laser power [W]
0
200
400
600
800
1000
Launched pump power [W]
Slope efficiency
40%
19%
Measured
Saturation curve fit

Fig. 2(b)



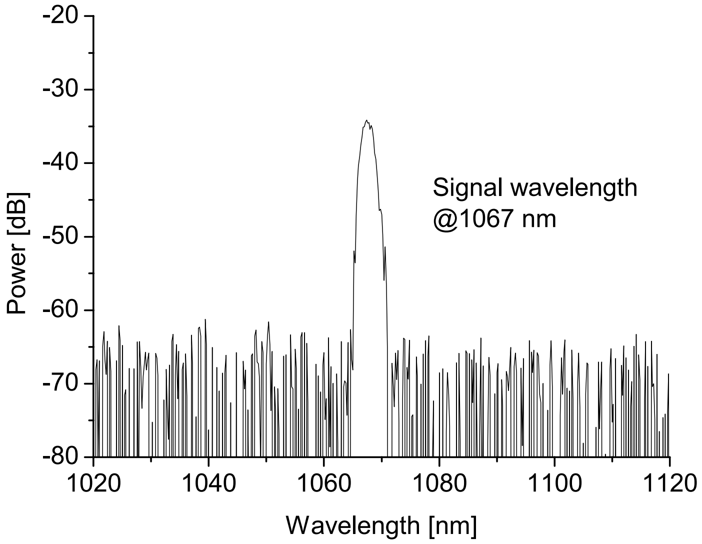
-20
-30
-40
-50
-60
-70
-80
Power [dB]
Signal wavelength
@1567 nm
1520
1540
1560
1580
1600
1620
Wavelength [nm]

Fig. 3(a)



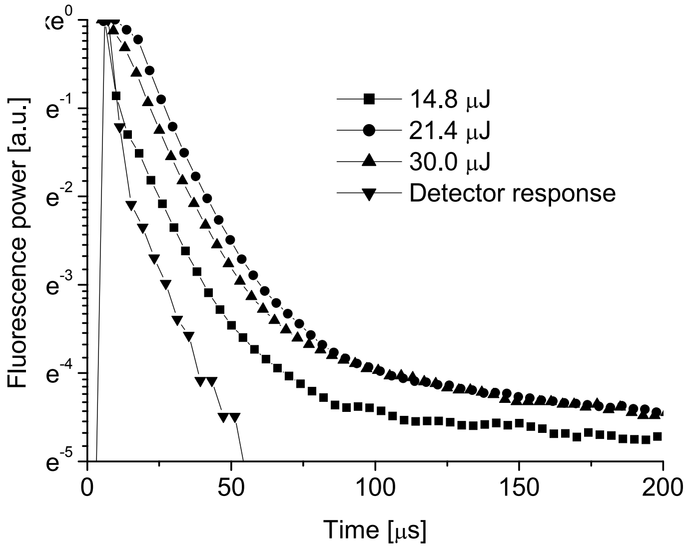
Measured (Total)
Linear fit
Slope efficiency: 42%
Forward
Backward
Laser power [W]
Launched pump power [W]
0
50
100
150
200
250
300
350
0
200
400
600
800
1000

Fig. 3(b)



Signal wavelength
@1067 nm
Power [dB]
Wavelength [nm]
-20
-30
-40
-50
-60
-70
-80
1020
1040
1060
1080
1100
1120

Fig. 4



e^0
e^-1
e^-2
e^-3
e^-4
e^-5
Fluorescence power [a.u.]
0
50
100
150
200
Time [μs]
14.8 μJ
21.4 μJ
30.0 μJ
Detector response