High Brightness Multi-Mode Fiber Lasers
A Novel Sources for in-Band Cladding Pumping of Singlemode Fiber Lasers

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Abstract: A novel design of multi-mode Er-doped fiber lasers operated in the spectral region of 1530-1600 nm have been proposed and realized. The lasers efficiency exceed 35-42% (depending on the wavelength), while maximum output power is limited on the level of 60 W only by pump power available in the experiment. The developed multi-mode laser can be used as an efficient high-power and high-brightness pump source for Er-doped (pump at 1530-1535 nm) and Tm-doped (pump at 1560-1600 nm) singlemode fiber lasers. Utilization of the same concept to the Yb-doped lasers could strongly accelerate output power growth of single-mode lasers in the 1 µm region as well.

1 INTRODUCTION

Resonant pumping is a promising approach in a development of kW-level single-mode fiber lasers. A small quantum defect allows one to obtain a high pump-to-signal conversion efficiency and, thus, to reduce a thermal load on an active fiber. There is a strong need in efficient and high-power sources at 1010-1040 nm for in-band pumping of Yb-doped lasers; at 1530-1535 nm – for pumping of Er-doped and at 1560-1600 nm – for Tm-doped fiber lasers (Zhang J., 2011; Jebali M.A., 2014).

However development of such sources is a challenging task by itself. For 1530-1535 nm spectral region (pump of Er-doped fiber lasers) a multi-mode semiconductor diode can be used. However, to the moment price, available power and electrical-to-optical efficiency of multimode diodes at 1532 nm significantly inferior to that of well-developed pump diodes at 980 nm. Another problem of such diodes is a thermal drift of central wavelength. The thing is in rather small (several nm) width of erbium absorption peak near 1532 nm. So, wavelength change with power can lead to decrease of pump absorption and efficiency rollover. Moreover, high power semiconductor diodes for longer wavelengths (1560-1600 nm) are not available at all.

Another option to build 1530-1600 nm pump laser is combining of several single-mode Er-Yb fiber lasers which in turn are pumped by 9XX diodes (Jebali M.A., 2014). However, output power of lasers based on commercially available single-mode Er-Yb fibers is limited by Yb emission near 1 µm at ~10 W level (Sobon G., 2014). So, although such pump source provides great wavelength stability and efficiency, it requires huge number of Er-Yb lasers (36 in ref. (Jebali M.A., 2014)) that significantly increase cost of the laser.

Development of pump sources operated in the spectral region near 1010-1040 nm is also not an easy task. Absence of efficient pump diodes in this region requires utilization of Yb-fiber lasers operated at this wavelength. However a specially developed large core-to-cladding ratio fibers are required to achieve a high inversion (to get a non-zero gain) and reasonable efficiency (Aleshkina S.S., Likhachev M.E., 2016).

The goal of our work is the development of compact and cheap pump source for in-band pumping of single-mode fiber lasers. The current communication is focused on the development of multi-mode Er-doped lasers for 1.5 µm region. However, we suggest that the same principles could be used for building of multi-mode pump source near 1 µm spectral range for in-band pumping of Yb-doped lasers.

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2 DESIGN OF THE PUMP LASER

2.1 Er-doped Multimode Fiber

As mentioned above, the output power of a laser at 15XX nm based on commercially available single-mode Er-Yb co-doped fiber is limited by parasitic lasing near 1 μm. A solution to this problem could be the utilization of Yb-free Er-doped double clad fiber as the active media for high power pump lasers near 1532-1535 nm (for Er-doped fiber lasers) or 1560-1600 nm (for Tm-doped fiber lasers). It was shown recently that such fibers are able to demonstrate optical-to-optical efficiencies up to 40% when pumped at 980 nm (Kotov L.V., 2013. Opt. Lett.). However, special design of these fibers is required. This design includes a large core diameter to provide high pump absorption, an optimized core composition (including low concentration of Er^{3+} ions) to suppress clustering. A fiber with a core diameter of 35 μm was proposed and realized in (Kotov L.V., 2013. Opt. Lett.). This core size was limited by the requirements of single mode operation and reasonably low bending loss. The maximum slope efficiency demonstrated with this fiber was 40 % and was achieved at an operation wavelength of 1585 nm. This source is suitable for pumping Tm-doped fiber lasers, but the long fiber length (~40 m) and a relatively high bend sensitivity (fiber should be wounded on a spool with 30 cm diameter) makes it rather cumbersome. Moreover the influence of clustering became much stronger for shorter wavelengths and results in a reduction of the efficiency down to 15 % near 1532 nm (ICONO/LAT). Thus, such lasers are not applicable for efficient pumping of the Er-doped single-mode fiber lasers.

On the other hand, there is no need for a high beam quality of the cladding pump for singlemode fiber lasers. The parameters of the fiber core are limited only by the requirement to match them to the pump ports of standard pump combiners: core/cladding diameters of 105/125 µm and numerical apertures (NA) of 0.15. Therefore, the active fiber core could be multimode and has diameter up to 105 µm. We performed a numerical analysis similar to (Kotov L.V., 2013. Opt. Lett.) to define the optimum erbium concentration. The signal grey loss was taken to be about 5 dB/km, pump loss – to be about 20 dB/km. The pump-to-signal slope conversion efficiency (PCE) of the amplifier based on co-propagating pump and signal power based on 60/125 μm and 90/125 double-clad Er-doped fibers operating at 1535 nm and 1585 nm were computed (Fig 1a). An efficiency of about 45% for signal at 1532 nm and 47% for signal at 1585 nm could be achieved. Wavelength dependence of maximum pump-to-signal conversion efficiency (PCE) is rather weak near the optimal concentration (see Fig.1b) and its maximum lies near 1565 nm wavelength.

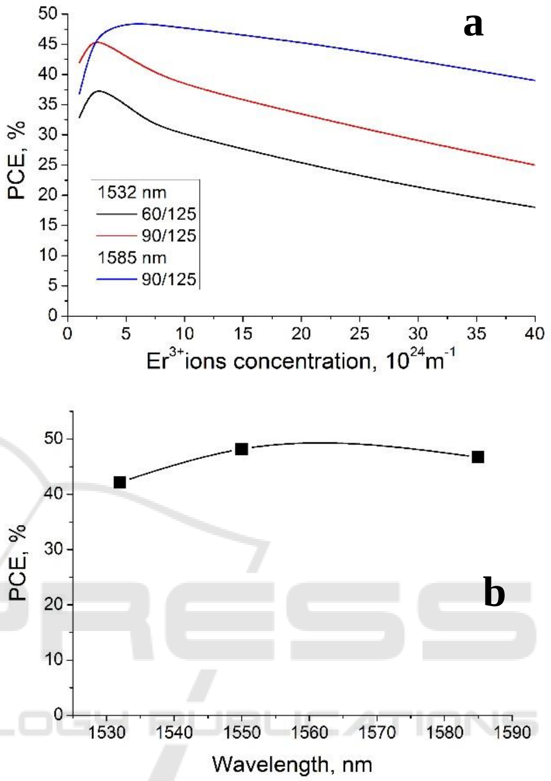

Figure 1: a - Computed pump-to-signal slope conversion efficiency (PCE) of the amplifier at 1532 nm and at 1585 nm for different Er^{3+} ions concentration and core/clad ratio; b – PCE dependence on wavelength for Er concentration about $7 \cdot 10^{24} m^{-3}$ and core/clad ratio as 105/125 µm.

Based on the simulation results, a fiber preform with aluminosilicate core and $\sim 4 \cdot 10^{24}$ m^{-3} Er^{3+} ions concentration was produced using the Modified Chemical Vapor Deposition (MCVD) technique. The preform was polished to an octagonal shape and double clad fiber was drawn down from it. The resulting fiber has core/cladding diameters of95/125 µm and was coated with polymer providing a pump NA of 0.46. Microscope image of the fiber facet is presented in Fig.2a. The refractive index profile (RIP) of the fabricated MCVD preform is presented in Fig. 2b. The core grey loss at 1200 nm was measured to be about 35 dB/km.

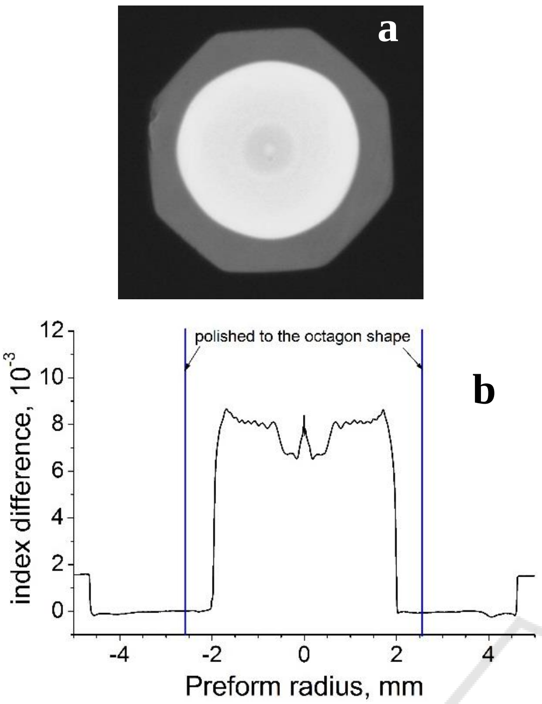

Figure 2: a - Microscope image of the fiber facet; b - Refractive index profile of the fabricated Er-doped preform.

2.2 Multi-mode Er-doped Fiber Amplifier at 1565 nm

At first the developed multi-mode Er-doped fiber was tested in a simple amplifier scheme, shown in Fig.3a. The standard 2+1-to-1 pump and signal combiner was used to deliver signal and pump into the Er-doped fiber. Signal fiber was standard single-mode 8/125 µm double clad fiber. The pump ports were based on standard 105/125 µm fiber. The pump module has maximum pump power of 50 W and it wavelength was stabilized at 976±0.5 nm by an internal volume Bragg grating. The pump combiner output was spliced to the developed multi-mode Er-doped fiber. The multi-mode fiber output was spliced to a standard multi-mode 105/125 µm fiber. A pump stripper similar to the described in (Aleshkina S., Kochergina T.A., 2016) was built at the splice point.

Our calculations has shown that the developed amplifier has the maximum efficiency when operates near 1565 nm. An Er-Yb laser with maximum output power of 0.5 W (limited by available isolator) was used as a seed source. The length of multi-mode Er-doped fiber was about 16.7 m that is close to the optimal one (according to our calculations). Dependence of output power at 1565 nm on pump power at 976nm is shown in Fig.3b. The dependence of output power on input signal (see Fig.3c) shows that the multi-mode fiber operated in saturation regime. Both dependences are fairly close to those, calculated using model and data (i.e. clustering level) from (Kotov L.V., 2013. Opt. Lett.) and actual parameters of the developed multi-mode fiber (core/clad diameters, Er-concentration and grey loss). The slope pump-to signal conversion efficiency was found to be as high as 42.4%, which is the highest ever reported value for high-power Er-doped fiber lasers pumped at 980 nm. It is still below the predicted maximum PCE (see Fig.1), which is caused by increase of grey loss from 5 to 35 dB/km. We suggest that improvement in preform production process would result in further increase for the PCE in the developed multi-mode fiber amplifier.

2.3 Multi-mode Pump Laser at 1535 nm

In addition to a high efficiency, there are other important demands for the pump source: compactness, high long-term stability, small size and low cost. The amplifier scheme presented in previous paragraph is quite efficient, but it requires operation of additional seed laser. Presence of the seed laser that is powerful enough to saturate the amplifier increases the cost and footprint of the system and makes it more cumbersome. Moreover, even in saturated regime the back-reflected signal can strongly affect the amplifier – a significant signal power might propagate in the backward direction in this case. Thus, it is preferable to keep power of the seed laser to be on the level of 4-10% of the output power to ensure a safe operation regime. When output power would grows to the level of 100 and even 200 W (see discussion section) the required seed laser power would exceed limit that is possible to achieve with Er-Yb lasers. By this reason in this section we propose a new laser design, free from aforementioned drawbacks.

The simplest and, therefore, the cheapest scheme for a fiber laser consists of a gain fiber spliced between two fiber Bragg gratings (FBGs). However, it is known that different modes have different reflection spectra from FBG written in multimode fiber. As a result, the spectrum of such a multimode laser has several peaks (Kurkov A.S., 2007), leading to effective spectral broadening. In addition, this effect could result in unstable operation because of mode competition. To ensure a narrow spectrum of a multimode laser, a master oscillator power amplifier (MOPA) scheme could be used.

In this work, we propose the new, simple multimode laser scheme shown in Fig. 4 a. A pump at

980 nm was launched into the cavity formed by 1.5 m of the single-mode double clad EDF developed in (Kotov L.V., 2013. Opt. Lett.) and a pair of FBGs. Four multimode pump diodes with an operation wavelength stabilized at 976 nm and overall maximum power of 173 W were coupled through a commercially available 7x1 pump combiner into the laser resonator. The FBGs were written in 20/125 passive fiber (NA~0.08/0.45) and had reflections of ~100 % and 10 % at 1535 nm with bandwidths <0.8 nm. The small-signal absorption from the cladding near 980 nm of the single-mode EDF is ~0.6 dB/m (Kotov L.V., 2013. Opt. Lett.), so only ~5 % of the overall pump power was absorbed in the single-mode laser cavity. It generated light at 1535 nm with a slope efficiency of ~45 % with respect to the absorbed power. This signal was used as the seed radiation for the 12 m piece of multimode EDF described above that was spliced to the 10 % FBG of the single-mode cavity. Commercially available 105/125 µm multimode fiber was spliced at the output of the laser, and a cladding pump stripper similar to that described in (Aleshkina S., Kochergina T.A., 2016) was built at the splice point. Therefore, the seed laser and amplifier were both pumped by the same pump diodes at 976 nm, and the spectral width of the laser was locked by the FBGs written in the single mode fiber, resulting in a relatively narrow output spectrum.

A specially developed multimode Tm-doped fiber was produced using the MCVD technique in order to protect the pump diodes from possible backward radiation near 1.5 µm. The fiber had a Tm-doped germanosilicate core and pure silica cladding with diameters of 105/125 µm and NA~0.22 (see insert to Fig4b). Thus, this fiber was matched to standard multimode pump fibers. The fiber loss was measured to be ~15 dB/m at 1535 nm and <70 dB/km at 976 nm (see Fog.4b). Two meter pieces of the Tm-doped fiber were spliced to each pump diode (not shown in Fig. 4 a). Due to the low feedback, large core diameter and long length of the Tm-doped fibers, the threshold for 2 µm lasing was orders of magnitude higher than the power of the potential back-propagating signal. Therefore, this signal would only be absorbed by the Tm ions and converted into spontaneous luminescence and heat. Thus, the developed Tm-doped fiber is an efficient pump protector for high power systems operating near 1.55 µm and pumped at 980 nm.

Fig. 5 a shows the output power of the developed multimode laser; 60 W of output power, which was limited by the available pump power, was achieved. The slope efficiency of the laser was estimated to be 35 %. The output spectrum measured over all spectral

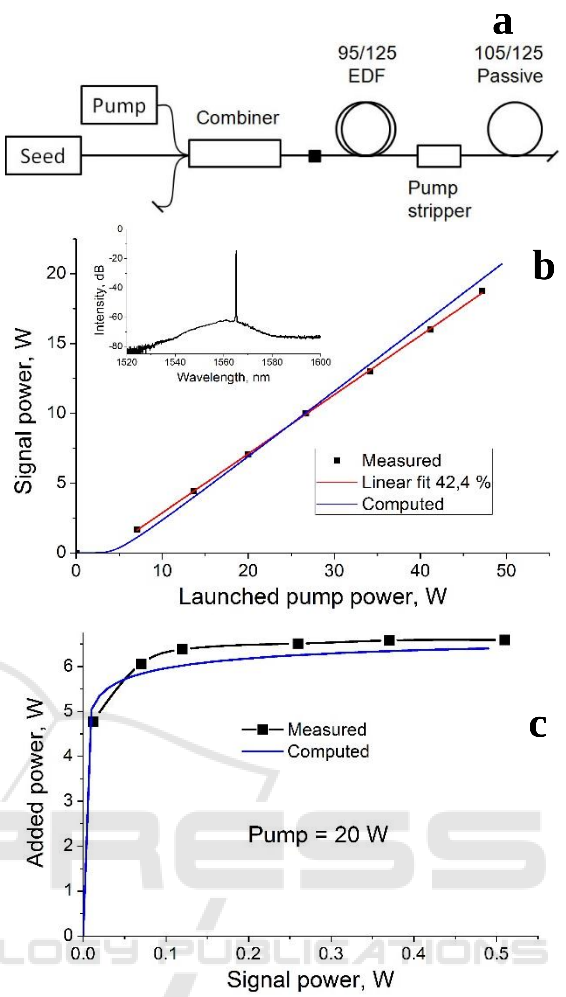

Figure 3: a - Scheme of the multi-mode Er-doped fiber amplifier; b – Dependence of the output power at 1565 nm on pump power, insert – output spectrum; c - Dependence of output power on input signal power at 1565 nm (pump power was fixed at 20 W). Blue lines – calculations, symbols – measurements.

range with 0.5 nm resolution is presented in the Fig. 5 b. A small part (~8 % relative to the output power of the laser) of unabsorbed pump at 976 nm was propagated in the multimode laser core together with the signal near 1535 nm. No active cooling was applied to the EDF during operation. Short-term temporal stability was investigated using a photodetector. A stable cw operation without self-pulsing was found (see Fig.5 c). Typical for all CW lasers noise on the time trace was caused by interference of different modes within 0.5 nm spectral bandwidth.

3 DISCUSSION

This work is devoted to a new concept of a multimode pump laser which could be used for in-band pumping of single-mode fiber lasers. Highly efficient operation is demonstrated for 1565 nm signal wavelength (suitable for pumping of Tm-doped fiber lasers) and for 1535 nm signal wavelength (suitable for pumping of Er-doped fiber lasers). An output power of 60 W at 1535 nm was achieved with a slope efficiency of 35 % with respect to the launched pump power at 976 nm. Taking into account the electrical-to-optical efficiency of the diodes at 980 nm (50 %), the overall "wall-plug" efficiency of the developed laser is ~17.5 %, which is fairly close to that of multimode diodes operating in this spectral region (25 %). Meanwhile, there are two serious advantages of the developed source over semiconductor pump diodes:

First, it has perfect output wavelength stabilization. The laser scheme includes FBGs written into single-mode fiber as a wavelength-stabilizing element. For this reason, the multimode fiber laser operates with a narrow bandwidth (~0.5 nm) at the chosen central wavelength independent of the output power. At the same time, thermal drift and a broad output spectrum are well-known problems of high power semiconductor diodes.

Second, the demonstrated power of 60 W is already higher than the values that could be found from commercially available multimode diodes at 1535 nm with 105/125 µm output fibers (typically ~ 30 W). The demonstrated output power is guided by the core with diameter of 105 µm and NA of 0.15. To the best of our knowledge obtained brightness of $7.66{\cdot}10^4$ $W/mm^2{\cdot}sr$ is the highest ever reported brightness for this spectral region.

Also it should be stressed that power of the proposed multi-mode fiber laser could be easy scaled. Indeed, only four of seven pump ports of the laser were utilized in the experiment. This means that using three additional pump diodes at 976 nm with the same power level it is possible to increase output power to more than 100 W power level. Moreover a 100 W multimode pump diode sources at 976 nm with 105/125 µm fiber pigtail are commercially available. Thus, the utilization of 7 of them and a 7 to 1 pump combiner allows one to achieve more than 200 W at 1535 nm from 105/125 fiber with NA=0.15 at the output of the multimode laser. Finally even this output power level from multi-mode fiber laser is not limited. As it was seen in Fig.1a the decrease of PCE is not very significant for Er-doped multi-mode fiber with core-to-clad ratio about 0.5 (60/125 µm). This means that multi-mode Er-doped fiber with core and clad equal to 100 and 200 µm could be realized and its PCE can be equal to 35% (same as in

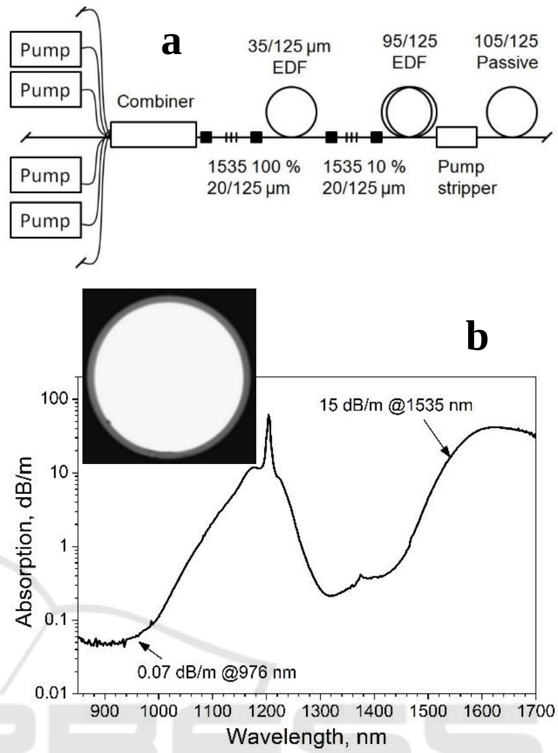

Figure 4: a - Scheme of the multi-mode Er-doped fiber laser; b – Absorption in the Tm-doped 105/125 µm fiber, used as pump protector; insert: Tm-doped fiber cross section.

current laser) if the fiber grey loss are optimized. Currently pump combiners with 19 pump ports (105/125 µm, NA=0.15) and output into fiber with outer diameter of 200 µm and NA=0.45 are commercially available. This means that there are no fundamental limitation to scale output power of multi-mode lasers at 1530-1590 nm (output inside 105/125 µm fiber with NA=0.15) to the level of 600 W of output power.

Utilization of such powerful pump sources instead of semiconductor pump diodes (Zhang J., 2011) or Er-Yb fiber lasers (Jebali M.A., 2014) could be very promising. In particular using of 7+1-to1 pump combiner and 7 such pump sources with a highly efficient in-band pumped Er-doped fiber laser (up to 75% PCE was demonstrated in (Jebali M.A., 2014)) could allow one to scale output power of the single-mode laser to the unprecedented level of more than 3 kW.

Same pump and laser design could be utilized for Tm-doped fiber lasers. Moreover a higher demonstrated PCE for the multi-mode Er-doped

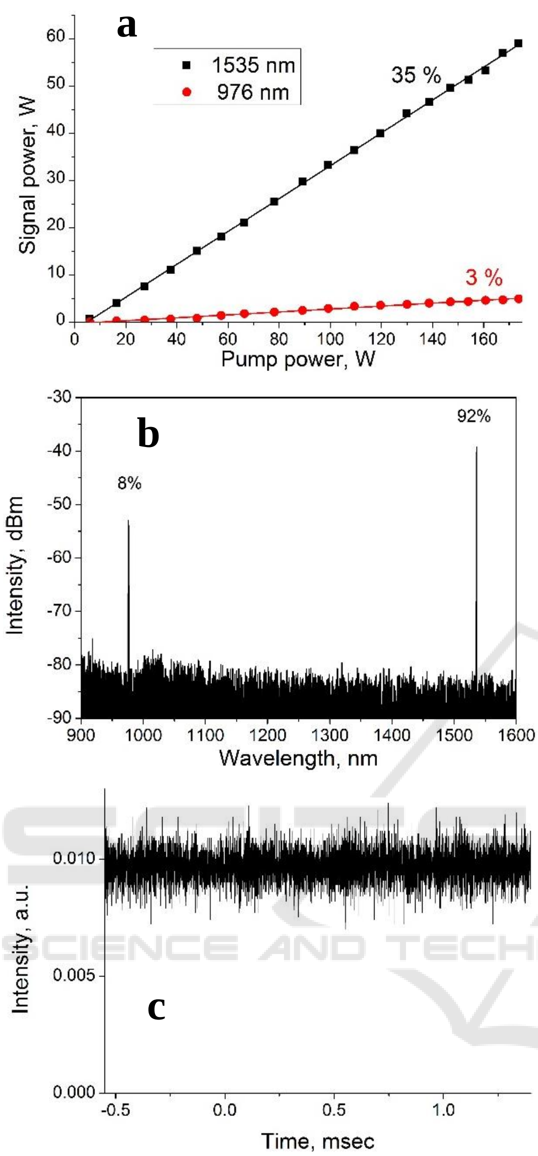

Figure 5: a – Dependence of the output power at 1535 nm and unabsorbed pump on pump power at 976 nm, b – Typical spectrum at the laser output, c – time trace from photodetector.

fiber laser operated at 1565 nm (42.4%) simplify power scaling to even higher level. Simple utilization of seven 100 W semiconductor lasers at 976 nm would allow one to achieve near 300 W output pump level. Optimization of parameters of Er-doped fiber with core and cladding diameters of 100 µm and 200 µm should allow one to increase output power to 800 W. A high in-band PCE efficiency of Tm-doped lasers (70% in (Shen D.Y., Sahu J.K., and Clarkson W.A., 2006)) can allow power scaling to almost 4 kW level.

Finally the power scaling of Yb-doped fiber lasers looks most promising with such laser design. In this case utilization of 100/400µm multi-mode Yb-doped fiber could allow one to realize few-kW multi-mode pump sources near 1.01-1.04 µm. In its turn utilization of such source to pump fiber laser, based on a perfectly single-mode (10..15)/(200..400) µm fiber can allow one scale output power of single-mode Yb-doped lasers to over 10 kW.

4 CONCLUSIONS

In conclusion, a simple, cheap and efficient scheme of the pump multimode laser has been proposed and realized. PCE of 35-42 % and output power up to 60 W was demonstrated with realized lasers schemes. Simple power scalability of such pump source is discussed. A new approach for the development of high-power, in-band pumped, single-mode fiber lasers is presented. Thanks to the easy power scalability of the developed system, few kWs-level single-mode Er-doped and Tm-doped fiber lasers near 1.55 µm could be realized in the near future. Possibility to apply the same laser concepts for the Yb-doped fiber lasers and scale output power of single-mode lasers to beyond 10 kW are also indicated.

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