YDFL Operating in the 1150-1200 nm Spectral Domain

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Abstract – **The family of the YDFLs operating in the range of 1147-1200 nm with the output power up to 35 W was realized. The ASE was analyzed and its origin was discussed in the frames of the inhomogeneous broadening concept; the parameter K describing ASE was introduced.**

Index terms – **Optical fiber lasers, optical fiber materials, fluorescence spectroscopy, infrared spectroscopy.**

I. INTRODUCTION

Yb-doped fiber lasers (YDFLs) currently are the most attractive type of fiber lasers owing to kW-range output optical powers, high efficiency, and direct diode pumping of low-brightness [1,2,3]. Also, a positive material dispersion allows to obtaine high-energy ultrashort pulses in the mode-locked lasers [4,5]. Currently the operating range of commercial YDFLs covers approximately 1050-1100 nm spectral window. Further expansion of this range is particularly interesting for a number of applications. These are for instance frequency-doubling (“yellow” light) [6, 7, 8] and optical pumping, i.e. pumping of Raman or Ho-doped fiber lasers [9, 10]. Alternative solutions, like e.g. Raman [11, 12] or relatively newly developed Bi-doped [13, 14, 15, 16] fiber lasers require a long fiber length and core-pumping, both considered as disadvantages for high-power lasers. The main problem in establishing such YDFLs is athe high ASE level and athe parasitic lasing at shorter wavelengths [17]. Special fiber design when the ASE is naturally filtered by the fiber improves the situation [18], resulting in 167 W of output power at 1178 nm, achieved in Yb-doped specialty photonic bandgap fiber amplifier with 5 W seed power [19]. However, the output powers of such fiber lasers without amplification are sufficiently lower. For instance, 10.8 W at 1180 nm were generated with the help of a photonic bandgap fiber [20]. Direct high power output from a laser is apparently attractive; also currently such specialty fibers are not commercially available. Simple step-index fiber technology is already well established. Several approaches helping to expand the operating range of such Yb-doped fibers have been reported: strong cavity coupling [21,22], core-pumping in the absorption tail [17, 23,24,25], active [17,25,26] and passive [27] heating of the active fiber and other techniques [28]. As a result, 10 W level of optical power has been successfully overcome. Thus, the output power of 12 W at 1178 nm was demonstrated for the core-pumped at 1090 nm YDFL [23]; actively heated up to 80^{o}C diode-pumped YDFL operating at the 1154 nm wavelength with 18 W of the output power was reported [26]. However, the question remains whether the further power scaling is possible and what are the factors helping or preventing it. Answering this important question is the main purpose of the paper.

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II. EXPERIMENTAL

We used Yb-doped aluminosilicate polymer-coated fibers in linear-cavity all-fiber YDFLs. Two fiber Bragg gratings (FBGs) UV-written in a specially selected SMF-28 fiber with a shifted to ~1.15 μm cut-off were spliced to the active fibers from both ends by an electrical fusion splicer and acted as a higly-reflective (HR) and an output coupler (OC). The spectral width of the couplers was less than 0.5 nm. The lasers operated either in open air or, for passive heating of the lasers, an active fiber was coiled on a thin plastic spool of about 1 cm height and placed inside a hand-made styrofoam box with a cover and a cavity perfectly matching the spool dimension. The temperature of the active fiber was monitored with a Ni-Cr thermocouple touching the fiber coil. The output lasers' spectra presented here were recorded with a spectrum analyzer with the roughest optical resolution of 10 nm to highlight the ASE relatively to the emission at the operating wavelength. The ASE fraction in the output emission was determined by a numerical integration over spectra. The output powers of YDFLs and pump lasers were measured by a power meter with an experimental accuracy of 5%.

The core-pumped YDFLs operating at 1160 nm wavelength were made with an Yb-doped fiber which had 7.5 and 125 μm diameters of aluminosilicate core and silica clad, respectively. The refractive index difference, Δn, between core and cladding amounted to 5×10^{-3}. The length of the active fiber used in the core-pumped YDFLs (see the Table) corresponded to the small-signal absorption of 18 dB. The fiber was pumped through a HR FBG spliced with an output fiber of a home-made YDFL producing unpolarized emission.

The clad-pumped YDFLs were made with a double-clad silica-based fiber consisted of two glass fibers joined in one polymer clad (GTW fiber [17, 29]) and acted as a conventional double-clad fiber. One of the fibers had a Yb-doped aluminosilicate core and a silica first clad of 14 and 125 μm diameters, respectively. The refractive index difference, Δn, between core and clad amounted to 3.5×10^{-3}. The second pure silica fiber had a diameter of 110 μm. Owing to a redistribution of the pump radiation between the touching each other fibers such construction allows to pump the fiber with a doped core by splicing the undoped fiber with a fiber output of a diode laser. Two diode lasers at the same time can be used being connected to both ends of the undoped fiber. Small-signal absorption coefficient at 915 nm wavelength amounted to about 1.2 dB/m.

Other parameters of the YDFLs are shown in the Table.

TABLE

OPERATING WAVELENGTH, Λ, PUMP WAVELENGTH ΛP, OUTPUT COUPLER REFLECTIVITY OC, ACTIVE FIBER LENGTH, L, SLOPE EFFICIENCY VS. LAUNCHED PUMP POWER, Η (AND VS. ABSORBED POWER IN BRACKETS), MAXIMUM PUMP POWER P_{IN}, MAXIMUM OUTPUT POWER P_{OUT}, ASE FRACTION IN THE MAXIMUM OUTPUT POWER AND INDICATION IF THE LASER EXPERIENCED HEATING OR NOT.

λ, nm	λ_p, nm	OC, %	L, m	η, %	P_{in}, W	P_{out}, W	ASE, %	Heating
1147	915	40	10	52	69	35	0.1	No
1147	975	40	10	60 (67)	27	15.5	0.05	No
1160*	1060	50	7	55	18	9	0	Yes
1160*	1066	50	9	52	19.5	8.8	0	Yes
1160	915	25	10	54	35.5	18	4	No
1160	975	25	14	60	36.5	21	0.2	Yes
1160	975	25	10	56	20.15	10.5	9	No
1180	915	60	10	31 (48)	35.5	10.5	2	Yes
1200	915	75	10	11**	2.9	0.11**	39	No
1353***	1147	20	400	38	14.5	5.2	–	–

*Core-pumped lasers
**ASE fraction is withdrawn from the output power
***Raman Fiber Laser

III. RESULTS

A. Core-pumped YDFLs

Although the YDFL pumped at 1066 nm did not demonstrate a laser action in open air, placed in the polyfoam box it operated in continuous-wave mode. Simultaneously, a heating of the active fiber was detected. At low temperatures the output power continued to increase (or decrease) during several minutes after a new pump power value had been adjusted. The time required for the stabilization of the output power became shorter at higher temperatures and became unobserved when the temperature was higher than ~ 90oC. At such temperatures a strong suppression (>10 dB) of an unabsorbed pump power was observed (Fig. 1). It should be the origin of a fast stabilization because further change of the absorption weakly affects the value of the absorbed pump power. At high temperatures the output power depended linearly on the launched pump power and the lasing efficiency of 52% was observed. Worth to note that the fraction of the unabsorbed pump power in the"cold" fiber was 66% and less than 1% at the maximum output power (Fig. 1) of 8.8 W. The full width at a half maximum (FWHM) of the laser line at the maximum output power was 0.15 nm and no ASE was observed (Fig. 1).

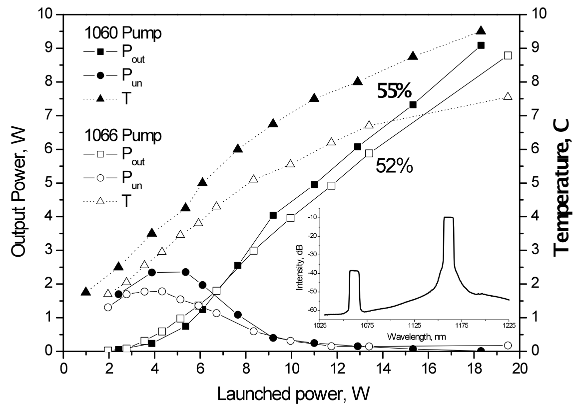

Fig. 1. Output laser power (P_{out}), unabsorbed pump power (P_{un}), and fiber temperature (T) vs. launched pump power. Spectrum of the laser emission at 7 W of the output power is shown in the inset.

The laser emission was frequency-doubled with a 30-mm long PPLN crystal with a fiber input. The maximum value of 760 mW of yellow radiation was obtained corresponding to 9% conversion efficiency. The FWHM of the 580 nm laser line was about 0.1 nm.

Change of the pump wavelength to 1060 nm lead to similar results reported in details elsewhere [27]. The efficiency and the output power reached 55% and 9.1 W, respectively; those ones for the frequency-doubled emission consisted of 10.6% and 860 mW, respectively. The fiber temperature was higher (Fig. 1) apparently due to a stronger heat production per unit length. The most important difference was that the laser action started also in the open air when the active fiber was tightly coiled [27]. This is the manifestation that the heat production per unit length is important to start the heating process.

B. Diode-pumped YDFLs

The main difference of the directly diode-pumped YDFLs was the presence of the ASE in their output emission spectra in the vicinity of the 1070 nm wavelength, Fig. 2. For the YDFLs operated at the 1147 nm wavelength in the open air the ASE level was negligible. The ASE behavior is analyzed in the separate chapter in what follows.

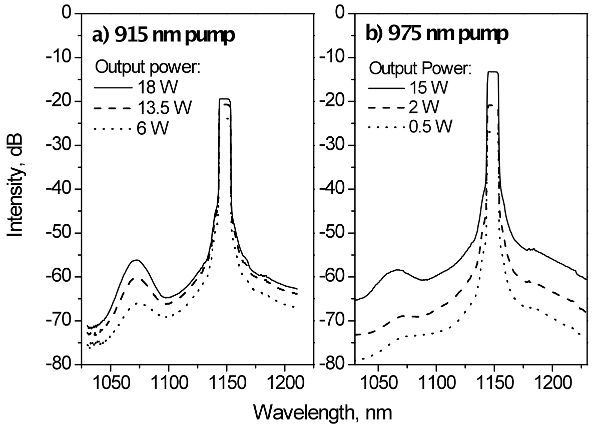

Fig. 2 Output spectra of YDFLs operating at 1147 nm wavelength: a) 915 nm, and b) 975 nm pump wavelength.

A linear approximation of the dependence of the output power on the launched pump power gives the slope efficiencies of 50-60%, see the Table and Fig. 3. Calculations relatively to the absorbed pump power in the case of 975 nm pumping gives the slope efficiency of 67%. The obtained output power of 35 W was limited only by the available pump power. At such power the FWHM of the laser emission was only 0.3 nm. To our knowledge, currently it is the most powerful YDFL operating in the vicinity of 1150 nm.

This laser was also was used for the pumping of a liner cavity single-cascade Raman fiber laser based on a phosphorosilicate fiber and operated at 1353 nm wavelength with the output power of more than 5 W (Fig. 3). Although its parameters were not optimized and thus the slope efficiency was moderate (38%), this is a good example of a practical application of such YDFLs because 1300-1400 nm spectral domain is of great interest in fiber optics.

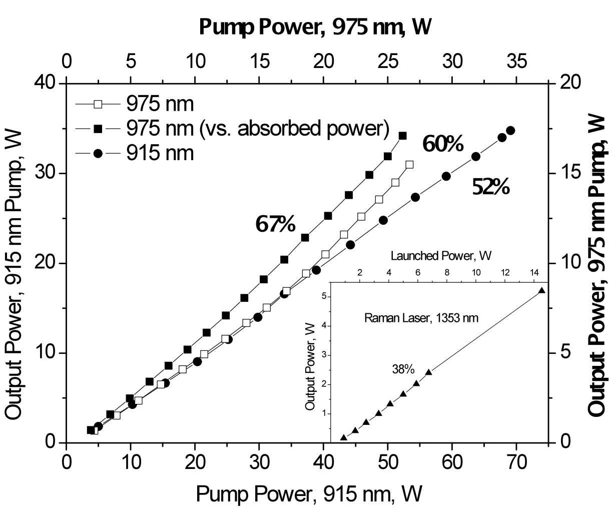

Fig. 3. Output powers vs. pump power for the YDFLs operating at the 1147 nm wavelength and for the Raman fiber laser operating at the 1353 nm wavelength (inset).

The tune of the operating wavelength to 1160 nm was made by the replace of the couplers of the laser. The lasers pumped at 975 and 915 nm wavelengths operated with similar efficiencies of 54 and 56% as it is indicated in the Table and Fig. 4. The highest output power 18W was limited by the available at the moment pump power. Due to a noticeable increase of the ASE intensity at this operating wavelength the 14 m long active fiber of another YDFL pumped at the wavelength of 975 nm was placed in the styrofoam polyurethane? box. Self-heating of the fiber resulted in a strong ASE suppression and the output power of 21 W was achieved. A slightly higher efficiency of 60% (Fig. 3 and the Table) resulted apparently from the longer fiber length providing better pump absorption. The linewidth (FWHM) at the maximum of the output power was about 0.15 nm. To our knowledge, it is the most powerful single-stage YDFL operating at 1160 nm.

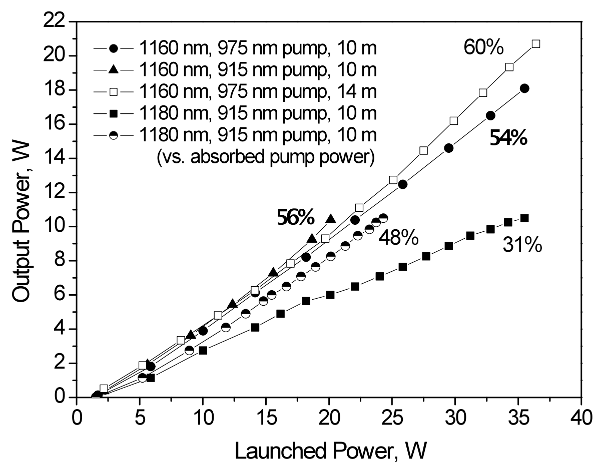

Fig. 4. Output powers vs. pump power for the YDFLs operating at the 1160 and 1180 nm wavelengths.

After a change of the pump power the ASE stabilized at a new level during several minutes evidently due to the establishment of a new temperature. Worth to note that the output power of the laser was remaining constant during the stabilization, Fig. 5, whereas the ratio between the fractions of the laser emission and ASE was varying. The same behavior was observed for the YDFL operated at 1180 nm.

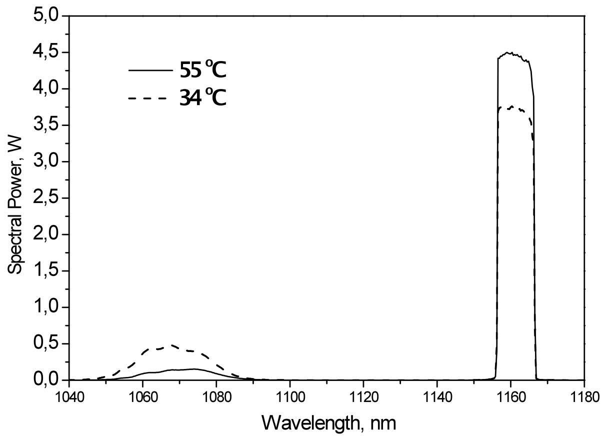

Fig. 5. Output spectra at different temperatures of the active fiber of the YDFL operated at the 1160 nm wavelength with the output power of 5 W.

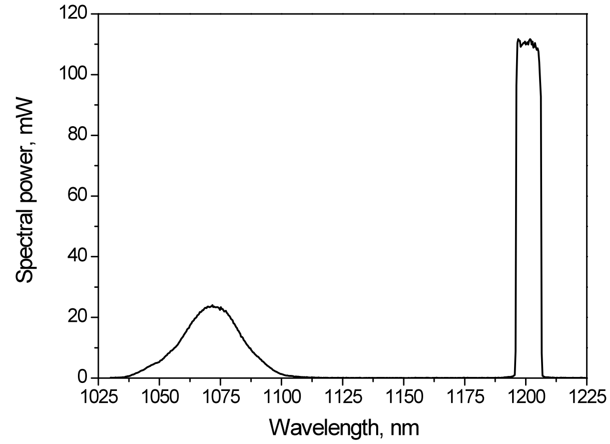

Fig. 5 Output spectrum of the YDFL operating at 1200 nm wavelength.

The YDFL operating at the 1180 nm wavelength was passively heated in the polyfoam box. At this operating wavelength a significant increase of the unabsorbed pump power, up to 32%, was observed evidently due to a smaller emission cross-section and a higher population of the excited state. The slope efficiency relatively to the launched pump power was 31% and noticeably higher, 48%, relatively to the absorbed pump power, Fig. 5. The output power reached 10.5 W limited also by the available pump power. The FWHM of the laser line was about 0.1 nm (the best resolution of the spectroanalyzer). To our knowledge, it is the most powerful diode pumped Yb-doped step-index fiber laser operating at 1180 nm.

The threshold of the YDFL operating at the 1200 nm wavelength was 1.9 W and the output power consisted of 180 mW at 2.9 W of the pump power. The FWHM of the laser line was less than 0.1 nm. The ASE fraction (Fig. 5) consisted of 39% (70 mW) what gives an estimation of the slope efficiency of 11% respectively to the radiation at 1200 nm wavelength (110 mW). Further increase of the output power was prevented by the parasitic laser action. No heating of the active fiber was observed apparently owing to a low thermal load of the fiber at the low pump powers. In spite of the low output power this result is considered to be quite promising because one can expect significant scaling of the output power and a strong ASE suppression with an active heating of the laser.

C. Efficiency at 1160 and 1200 nm

A general tendency of ASE for the YDFLs operated in open air was the rise in magnitude with increase of the pump power and the operating wavelength, Fig. 2. At the maximum output power at the operating wavelength of 1147 nm the ASE fraction in the output emission was less than 0.05 and 0.1 % for 975 and 915 nm pump wavelength, respectively. Change of the operating wavelength to 1160 nm resulted in the ASE fraction increase in more than an order of magnitude, see the Table.

Experienced sufficient heating YDFLs demonstrated more complex behavior. ASE fraction at different output powers for such YDFLs is shown in Fig. 6. In the inset the fraction after thermal stabilization of the lasers is shown (except for the point at 0.6 W of the 1180 nm YDFL obtained by a fast decrease of the pump power.)

As it is seen from Fig. 6, the ASE fraction for the passively heated YDFL operated at 1160 nm wavelength had a non-linear dependence on the pump power. During thermal stabilization, the ASE fraction was changing in a wide range. It changed from 15 to 8% at 2 W of the output power as the fiber heated up from 30 to 40°C. At a higher output power this range becomes broader: at 5 W the ASE fraction changed from 22 to 7% with the corresponding temperature change from 34 to 55°C. However, the temperature dependence remained just the same, about 0.7%/°C.

It is interesting, that a longer fiber length produces stronger ASE in spite of the expected increase of the ASE reabsorption. Thus, the ASE fraction in the output power of the YDFL with the active fiber of 14 m length at 34°C and 5 W of the output power was 22% (Fig. 6) which is higher than in the YDFLs operated in the open air, see the Table.

At the output power of 21 W the ASE fraction in the output laser power becomes negligible, about 0.2%.

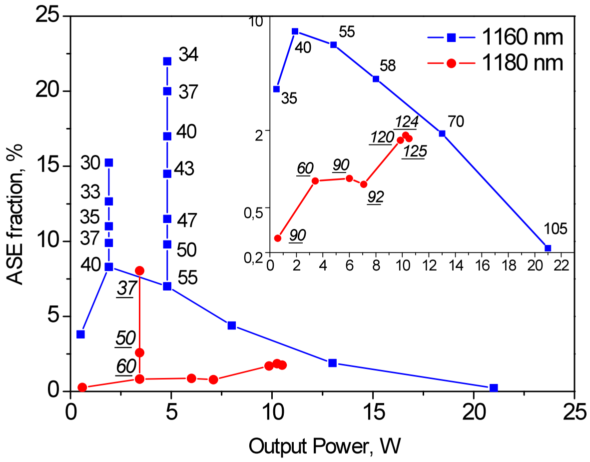

Fig. 6 ASE fraction of the YDFLs operating at 1160 and 1180 nm wavelengths. Near the points in the graph the corresponding temperatures of the fiber are shown.

In contrast to the 1160 nm YDFL, ASE fraction for the YDFL operating at 1180 nm wavelength almost monotonically increased with the increase of the output power. Being low near the threshold (<0.3%) which is evidently originated from the strong cavity coupling it increased to 2% at the output power of 10.5 W as it shown in the Fig. 6. It also was suppressed by the heating, Fig. 6, but the suppression was weaker than in the previous case. At 3 W of the output power it changed from 8 to 1% when fiber temperature changed by 23°C. It is about 2 times slower (0.3%/°C) than in the previous case.

IV. DISCUSSION

Analysis of the results shows a general tendency: at the same temperature (for example, 90°C for 1180 nm YDFL or 35 and 40°C for 1160 nm YDFL, Fig. 6), the fraction of ASE is higher at a higher pump power. Although this has been already known, the result is somewhat surprising because in the steady-state the cavity coupling controls the gain and subsequently the population of the excited state if the medium is homogeneously broadened. But, the rise of ASE means that the gain in this ASE spectral region also rises with the pump power. There can be two speculative explanations for the gain rise: a violation of the steady-state approach and/or an inhomogeneous spectral broadening of the gain. Here the latter concept is referred as it is well known [1] that the spectra of rare-earth ions in glasses are inhomogeneously broadened.

Here it is proposed that a relative deviation of the ions emission cross-section from the average is stronger expressed in the tails of the emission band than in its center, Fig. 7. At the threshold the lifetime in the excited state is determined by the spontaneous emission been known to be equal for all ytterbium ions. Far from the threshold, however, the main factor becomes the stimulated emission and those ions with smaller emission cross-section spent more time in the excited state so their fraction becomes bigger. To maintain the gain at the operating wavelength, the total number of ions in the excited state also should become bigger than at the threshold. Because the number of ions in the excited state rises, the gain in the ASE domain where the mean deviation of emission cross-sections is smaller also rises.

Worth to note that due to a small emission cross-section in the emission tail [26,30] the gain for ASE at the threshold is already quite high for an usual coupling of several percents. Just for demonstration, for a well inverted laser medium the gain per one way cavity trip would be about 70 dB at 1070 nm wavelength for the YDFL operated at 1160-1180 nm wavelength with a normally cleaved fiber end as an OC, what is apparently unrealistic. The strong coupling improves this particular situation [21].

Because the cross-section deviation from the average value (Fig. 7) is stronger in the tail of the emission band the ASE gain is also higher at the longer wavelength. Thus, in spite of higher temperatures and stronger coupling, the tendency of the ASE to rise overcomes its temperature suppression for the 1180 nm operating wavelength in contrast to the 1160 nm one, Fig. 6.

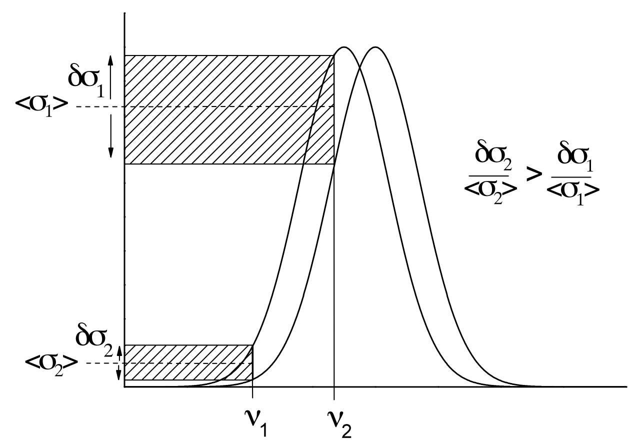

Fig. 7. Inhomogeneous broadening and deviation ($\delta\sigma_1$ and $\delta\sigma_2$) of the emission cross-section from the average value ($\langle\sigma_1\rangle$ and $\langle\sigma_2\rangle$) near the center of the emission band (ν_1) and in its tails (ν_2) shown for a band consisting of two components.

For a better understanding let us simplify the situation with the inhomogeneous broadening and assume that the sum σ_s of the absorption and emission cross-sections is nearly the same for all the ions at the pump wavelength, as well as in the ASE domain; whereas the emission cross-section at the operating wavelength σ_e has a noticeable deviation among the ions from the mean value. Neglecting the absorption cross-section (which is more than three orders of magnitude smaller than the emission cross-section) at the operating wavelength it is possible to write down for a subset of the ions characterized by the emission cross-section σ_e in the small volume of the medium:

$$n_2 = n_0/(1 + I_g/I_p\times(I_s/I_g + \lambda_g/\lambda_p\times(\sigma_e/\sigma_s))),$$

where n_2 is the concentration of the ions in the excited state; n_0 is the maximal concentration of the ions in the excited state (which is dependent on the cross-sections at the pump wavelength only); I_s is the saturation intensity; I_g is the laser field intensity; I_p is the pump field intensity; λ_g is the operating wavelength, and λ_p is the pump wavelength.

At the threshold $n_2 = n_0/(1 + I_p/I_s)$. So, the fraction of the ions in the excited state is equal for all the ions' subsets. Far from the threshold, where $I_g >> I_s$, and I_g /I_p is constant

$$n_2 = n_0/(1 + I_g /I_p\times \lambda_g/\lambda_p\times\sigma_e/\sigma_s).$$

So, the fraction of the ions in the excited state is different for the subsets with different σ_e. The parameter

$$K = I_g /I_p\times \lambda_g/\lambda_p\times\sigma_e/\sigma_s \quad (1)$$

shows if the ASE is the issue in the laser (K>>1 or K~1), or not (K<<1).

Let us consider first the situation when K>>1 which can be actual for the case of clad pumping when $I_g /I_p >> 1$. This situation is the worst because the difference in the fractions in the excited state for different subsets is maximal. For instance, for two subsets of the same concentration n_0 but with different emission cross-sections σ_{e1} and σ_{e2} the difference in the fractions in the excited state n_{21} and n_{22} is $n_{21}/n_{22}= \sigma_{e2}/\sigma_{e1}$. Thus, if the cross sections differ in an order of magnitude then the fraction in the excited state in the subset with the smaller cross-section is also ten times bigger. Just for demonstration let us suppose that there are only these two subsets in the medium. As the gain per unit length for the four-level scheme (long operating wavelength) is a product of emission cross section and the concentration, it is easy to show that the total concentration of the ions in the excited state is approximately 3 times higher far from threshold than near it.

The condition at which the number of ions in the excited state well above the threshold is minimized corresponds to K<<1. For simplicity the term $\lambda_g/\lambda_p \sim 1$ in Eq. 1 can be omitted:

$$K \approx I_g /I_p\times\sigma_e/\sigma_s .$$

For the operating wavelengths of 1160 and 1180 nm and for the pump wavelength of 975 nm the cross-sections ratio is quite low $\sim 4\times10^{-3}$, being about an order of magnitude bigger at the 915 nm pump wavelength, $\sim 3\times10^{-2}$. The accurate calculations should take into account also the actual spectral width of the pump radiation increasing this ratio in the case of the narrow 975 nm absorption peak.

The ratio of the radiation intensities in the case of the clad-pumping is, in contrast, high. Assuming the powers to be comparable and taking into account only geometrical factors, for the clad and core of 125 and 5 µm diameters one obtains $I_g /I_p \sim 6\times10^2$. The pump depletion along the fiber length and the strong coupling can sufficiently increase it thus working in the negative manner. So, the issue with a strong coupling is not as simple as it seems to be from a first glance. It is guessed that for the conventional parameters of the step-index Yb-doped double-clad fibers K > 1.

The important conclusion is that for a certain pump and operating wavelength only the ratio of the radiation intensities I_g /I_p influences the ASE. This ratio is smaller in average for a smaller fiber length owing to lower pump absorption and consequently higher average pump intensity. Also, the decrease of the first clad diameter and the increase of the core size would be beneficial. As the first parameter seems to be more or less stabilized (100-200 µm), the latter can be sufficiently improved. Thus, using large-mode area fibers it would be possible to sufficiently reduce if not eliminate the ASE in 1160-1180 nm domain and move high-power lasers at even longer wavelength which is planned for future.

In respect to the case of the core-pumping, although the cross-section ratio is degraded up to $\sim 10^{-1}$, the intensity ratio is sufficiently improved, $I_g /I_p \sim 1$. As the result, the ASE was not observed in the core-pumped YDFLs output at all. But, a fast decrease of the absorption coefficient makes it necessary to pump the fiber in the core, so this technique is questionable for high-power lasers.

This situation can be further improved by changing the ratio between absorption and emission cross-sections and thus diminishing the gain in the unwanted spectral domains by heating the fiber [25]. Self-heating of the fiber is proved to be an advantageous technique due to simplicity and reliability of the laser construction. However, heating has some physical limits; at least a conventional fiber coating is thermally damaged at the temperatures higher than 200-250°C.

So, we believe that the combination of the approaches, mostly heating and the fiber design, will allow further scalability and extension to longer operating wavelengths.

V. CONCLUSION

The family of the YDFLs based on the simple step-index Yb-doped fibers and operated in the range of 1147-1200 nm was realized. The high-power clad-pumped YDFLs operated at 1147, 1160 and 1180 nm with the output powers of 35, 21 and 10.5 W, with the slope efficiencies of 52, 60 and 31% relatively to the launched pump power and the negligible ASE fraction of 0.1, 0.2 and 2%, respectively. The output powers were limited by the available pump power only. Operation at 1200 nm of the clad-pumped YDFL was demonstrated with the output power of 110 mW and the slope efficiency of 11%. To our knowledge, these powers are the highest reported for the directly diode pumped Yb-doped step-index fiber lasers operating at the specified wavelengths.

The applications of such lasers, pumping the Raman fiber laser operating at 1353 nm with the output power of more than 5 W, and the second harmonic generation at 580 nm with the optical power of 860 mW are demonstrated.

The ASE origin was analyzed and discussed in the frames of the inhomogeneous broadening concept. It was concluded that the number of the ions in the excited state rises with pumping rate thus increasing the gain in the ASE domain. The rise is simply described by the parameter $K = I_g/I_p\times\lambda_g/\lambda_p\times\sigma_e/\sigma_s$. It is maximal when K>>1 and negligible when K<<1. It was also shown that shorter fiber lengths and larger core sizes are beneficial for a successive operation of the YDFLs in the long-wavelengths domain.

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