CW 1.06-μm pumped Ytterbium-Holmium co-doped all-fiber laser for 2.05 μm

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ABSTRACT

An Ytterbium-Holmium co-doped all-fiber CW laser is reported. The fiber used in the laser setup has been fabricated through the conventional MCVD process in conjunction with the SD technique and finally drawn using a standard fiber-draw tower. The laser was built in a linear Fabry-Perot configuration in which two fiber Bragg gratings reflecting at 2.05 μm were used as the cavity couplers. Under 1.06-μm in-core pumping of the fiber, CW lasing at 2.05 μm was provided due to energy transfer $Yb^{3+} \rightarrow Ho^{3+}$. The laser demonstrated low threshold (~0.8 W), moderate slope efficiency of lasing (~8.4% when measured *vs.* pump power launched into the active fiber), and high stability: during 6 hours its output power fluctuated within a 3% range. The laser spectrum width at a 3-dB level using an optical spectrum analyzer with a 37-pm resolution was measured to be ~70 pm.

Keywords: 2 microns, Ytterbium-Holmium co-doped silica fiber, Fabry-Perot cavity, CW operation

1. INTRODUCTION

Lasing beyond 2 μm by using Holmium (Ho^{3+}) doped silica fibers (HDFs) as an active medium is currently a progressively developing research area, given attractive perspectives of utilizing >2-μm coherent radiation from a fiber-based laser, both continuous-wave (CW) and pulsed, for versatile applications such as medicine (lithotripsy), eye-safe lidars, new telecom channels, *etc*. Considerable success in the area reached in the last few years[1-12], in terms of increasing output power and efficiency of Ho^{3+} doped fiber lasers (HDFLs) and their operation regimes, on one hand, and enriching knowledge about the physical challenges that still exist, on the other hand, deserves emphasis.

One of the challenges is the choice of a pump design for a HDFL: Vast majority of the reported ~2-μm HDFL systems are pumped either 'in-band' of the Ho^{3+} ion, through transitions $^5I_8 \rightarrow {}^5I_6$ (~1.15 μm) and $^5I_8 \rightarrow {}^5I_7$ (~1.95 μm), or, while using Thulium (Tm^{3+}) co-doping, into ~0.79-μm band of the Tm^{3+} ion (transition $^3H_6 \rightarrow {}^3H_4$), provided the existence of an effective energy-transfer (ET) channel $Tm^{3+} \rightarrow Ho^{3+}$ to manifold $^5I_7$ of the latter ion. In the meantime, it deserves mentioning Yb^{3+}, Ho^{3+} co-doped silica fibers (YHDFs) as one more candidate for >2-μm lasing (through Ho^{3+} transition $^5I_7 \rightarrow {}^5I_8$) while exploiting the ET process $Yb^{3+} \rightarrow Ho^{3+}$ via the 'indirect' excitation[13] $^2F_{5/2}$ (Yb^{3+}), $^5I_8$ (Ho^{3+}) $\rightarrow$ $^2F_{7/2}$ (Yb^{3+}), $^5I_6$ (Ho^{3+}) (when the Yb^{3+} subsystem gets inverted once pumped through Yb^{3+} transition $^2F_{7/2} \rightarrow {}^2F_{5/2}$), followed by fast non-radiative relaxation $^5I_6 \rightarrow {}^5I_7$ (Ho^{3+}). Itself, interest to YHDFs[13-16] stems from general understanding of the extraordinary properties of the Yb^{3+} ion as unique among other rare-earth ions doping silica matrix in the sense that it has the highest absorption and emission cross-sections, is characterized by a minimal Stokes defect when pumped and by the absence of excited-state absorption (ESA), given by its 'two-level' scheme, and also because Yb^{3+} can be embedded into silica glass up to high concentrations. At the same time, Yb^{3+} ions are known to be an attractive sensitizing agent providing, through a kind of the mentioned ET mechanisms, indirect excitation of a variety of rare-earth ions such as Er^{3+}, Ho^{3+}, and Tm^{3+}, in turn capable of lasing at longer than 1-μm wavelengths. However, attention to the 'YHDF-based laser (YHDFL) concept' – that is, the use of YHDFs for >2-μm lasing at indirect excitation – has demonstrated historically growth and fade (*i.e.* a little of newer data published in the past few years). Moreover, the concept was even not mentioned in the recent review[17], sketching the current trends towards effective mid-infrared lasing using fiber lasers. Most probably, this happened because a sole study[13] so far published on the theme, *viz*., ~2.1-μm lasing by means of the use of a double-clad YHDF at diode pumping at 978 nm, has shown a pretty low optical-to-optical efficiency of the system (~2.4% while consuming ~50 W of incident pump power) and, as far as we know, no further results on optimizing the 'YHDFL-concept' were reported.

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Our present report serves for the concept's 'refreshment', suggesting another route of the YHDF system's excitation, namely, pumping of such fiber by an Yb^{3+} doped fiber laser (YDFL) operated at a 'common', 1.064-µm, wavelength. In difference to the paradigm[13], our YHDFL was implemented in all-fiber configuration, more relevant for the 'tandem' designs. Note that the basic output parameters of our laser were not subject of optimization; meanwhile its optical-to-optical efficiency was measured to be a few times higher than that reported[13], even though if one takes into account common efficiency of the YDFL pump (~75%). Let's also emphasize brightness of the released ~2.05-µm (noteworthy, CW) radiation from the YHDFL, given by its narrow-band spectrum (measured to be ~70 pm in the whole pumps' range available) and long-term (a few hours per-a-day) stability of the regime.

2. EXPERIMENTAL SAMPLES AND SETUP

The home-made YHDF we experimented with has been fabricated through the standard MCVD process employed in conjunction with the SD technique and finally drawn using a standard fiber-draw tower. The YHDF's basic parameters are as follows: Outer clad and inner (doped core) diameters ≈123.8 µm and ≈5.7 µm, correspondingly; $\Delta n \approx 6\times10^{-3}$; cutoff wavelength ≈0.97 µm; NA ≈0.13. These parameters provided single-mode propagation of both the pump and signal (laser) waves in the YHDF. The doping levels of Yb_2O_3 and Ho_2O_3 are, respectively, ~6.0 wt.% and ~0.6 wt.% (the co-dopants enrich the core glass at a ≈10/1 ratio) and those of Al_2O_3 and GeO_2, introduced into the core glass for engineering Δn and also (Al_2O_3) for diminishing the rare-earth ions' clustering, are respectively ~2.0 wt.% and ~0.5 wt.%. Note that the YHDF supports single-mode propagation nearby the laser wavelength, λ_g ≈2.05 µm (see below). For comparison, we handled in experiments the home-made HDF sample (free from Yb^{3+} co-doping), having similar to the YHDF Ho^{3+} content (~0.7 wt.%) and comparable waveguide parameters, and also the sample of purely Yb^{3+} doped fiber (YDF) of the *YB2000-6/125DC* type (*Liekki*) with Yb^{3+} concentration and absorption in 978-nm Yb^{3+} peak (~2000 dB/m) comparable with those in the YHDF.

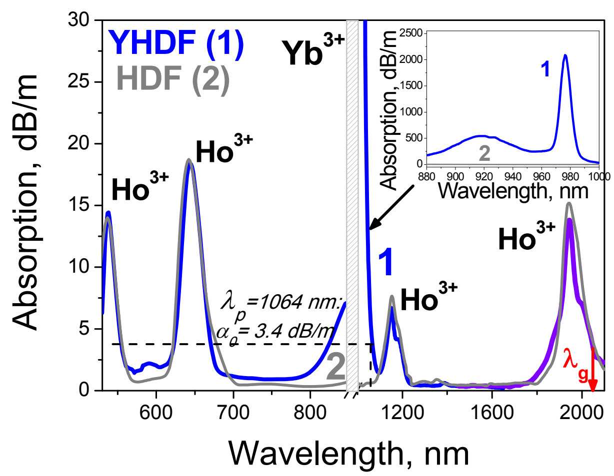
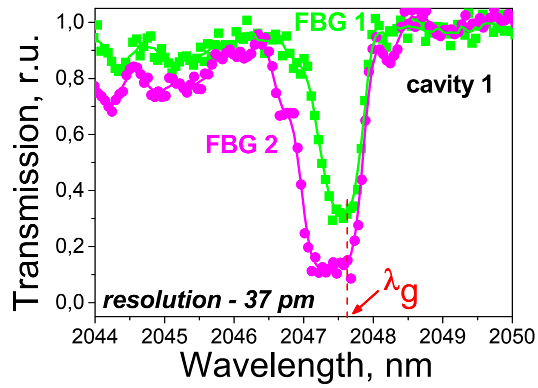
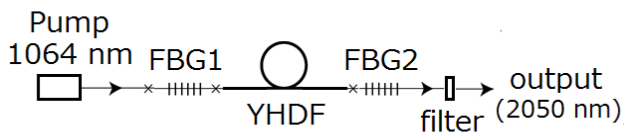


Figure 1. Attenuation spectra of the YHDF (curve 1) and HDF (curve 2); λ_P and λ_g mark the spectral positions of pump (1.064 µm) and generation (~2.05 µm). Inset specifies the Yb^{3+}-band.

As seen from Fig. 1, where we present the YHDF absorption spectrum (blue curve 1), the Ho^{3+} bands structure is 'common' (compare with the analogous absorption spectrum of the HDF sample shown by grey curve 2), being composed of the near- and mid-IR bands centered at ~1.15 µm and ~1.95 µm and a row of bands in the visible. The YHDF's absorption spectrum also demonstrates the intensive Yb^{3+} band centered at ~980 nm (see the figure's break, featured in the inset), which is absent in the HDF's one. The IR bands' maxima are seen to be measured by ~2100 dB/m (~978 nm: Yb^{3+} transition $^2F_{5/2} \rightarrow {}^2F_{7/2}$), ~7 dB/m, and ~14 dB/m (~1.15 and ~1.95 µm: Ho^{3+} transitions $^5I_8 \rightarrow {}^5I_6$ and $^5I_8 \rightarrow {}^5I_7$), correspondingly. What is relevant for further discussion of ~2-µm lasing when using the YHDF is the value of its 'small-signal' absorption coefficient (α_0) at the pump (1.064-µm) wavelength, measured to be ≈3.4 dB/m; see the dashed line in Fig. 1 marking this value.



(a)



(b)

Figure 2. (a) experimental setup; (b) transmission spectra of FBGs (1 and 2) forming cavity 1.

The experimental setup employed for studying ~2-μm lasing is sketched in Fig. 2 (a). A simple set of the components forming, while spliced, the fiber laser comprised a pump laser with fiberized output (*IPG-Polus*: model PYL-10LP, delivering in our case nominal power ~7.5 W at wavelength 1.064 μm), a piece of the YHDF, and a couple of home-made fiber Bragg gratings (FBGs) inscribed in a standard SMF fiber, selectively reflecting at ~2.05 μm, which served as the cavity's rear (FBG 1) and output (FBG 2) couplers. Notice that no isolator was used in between the pump laser and the YHDFL. The measured transmission spectra of one of the FBGs' pair, employed in experiments, are demonstrated in Fig. 2 (b), which reveal the reflection coefficients at ~2.045 μm to be ≈92% (FBG 1) and ≈72% (FBG 2), respectively; the other pair of FBGs employed in experiments provided the reflection coefficients at ~2.047 μm of ~90% (FBG 1) and ~12% (FBG 2). The cavity composed of the first FBGs' set is referred further to 'cavity 1' whilst the one composed of the second FBGs' set – 'cavity 2'. A dichroic filter (*Thorlabs*: model FEL1100) was placed on the YHDFL output when performing the spectrally-selective measurements; it provided cutting off the pump (at 1.064 μm) contribution at a >~20-dB level, while transmitting ~2.05-μm (the YHDFL's working wavelength) light at a ~65% level. The output parameters of the YHDFL were measured by means of a photo-detector (PD) sensitive to ~2-μm radiation (*New Focus*: model 2034), an oscilloscope (*Tektronix*: model TDS 3032), a pair of optical spectrum analyzers (OSAs) with fiber inputs (*Thorlabs*: model 203, for 1.0–2.5-μm spectral range, and *ANDO*: model AQ-6315-A, for 0.4–1.6-μm spectral range), and a power-meter (PM) (*Thorlabs*: model S314-C). In experiments we varied the pump power and the YHDF length, in order to seek for more physics that stands behind the laser's functionality.

3. RESULTS AND DISCUSSION

In Fig. 3, the dependences of ~2.05-μm output from the laser (measured using PD with >~20-dB filtering of 1.064-μm pump remnants) on pump power (P_P) are exemplified for the two cavity implementations: (a) cavity 1 and L_{YHDF} =5.0 m and (b) cavity 2 and L_{YHDF} =10.5 m.

It is seen that the threshold powers are, correspondingly, ~0.8 W and ~2.0 W (marked by vertical dashed arrows) and that the dependences are linear *vs.* P_P, (*i.e.* its part launched into the YHDF) after crossing thresholds by the YHDFL. The maximal ~2.05-μm output powers P_S (measured using PM at launched in YHDF core pump power, P_P ≈6.5 W) were ≈0.41 W and ≈0.26 W, respectively. The left-corner insets in Fig. 3 (a, b) demonstrate 1-ms snapshots of the PD signals, captured in the whole 1.064-µm pump range, reveal the absence of pulsing and, therefore, essentially CW operation of the laser in both implementations. This is also confirmed by the FFT analyses of the snapshots, showing the absence of pump-dependent relaxation-frequency peaks, usually attributing self-Q-switch effects arisen due to the ESA or rare-earth ions' clustering phenomena. In turn, the right-corner insets in the figures demonstrate optical spectra of lasing (recorded using OSA turned to its best resolution, 37 pm) near thresholds. In both cases, the laser lines, centered at wavelengths λ_g ≈2.045 µm (cavity 1) and ≈2.047 µm (cavity 2), were measured to be ~65 pm at a 3-dB level. Noteworthy, the laser lines' widths changed negligibly in both cavity implementations at increasing P_P up to maximum, being <70 pm.

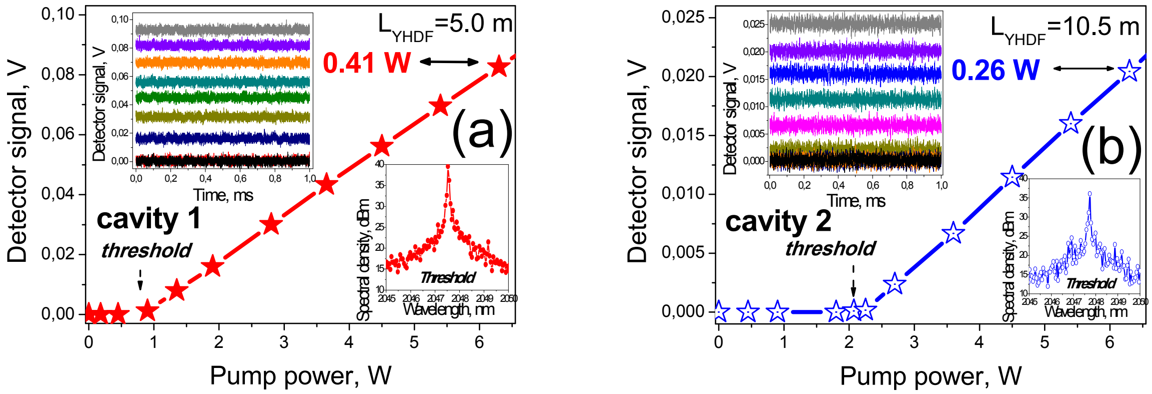


Figure 3. Dependences of ~2.05-µm output of the YHDFL on pump power in the cases of: (a) cavity 1 (L_{YHDF} = 5.0 m) and (b) cavity 2 (L_{YHDF} = 10.5 m). Upper left-hand insets demonstrate 1-ms PD snapshots at different pump powers (shown by different colors); lower right-hand insets specify optical spectra of lasing nearby thresholds (resolution, 37 pm), marked by arrows.

Overview of the basic parameters of the YHDF lasing, being (a) threshold power, (b) 1.064-µm pump remnants at output, (c) slope efficiency, and (d) ~2.05-µm power, is given by Fig. 4 (the red 1 and blue 2 curves on its panels adhere to the cavity implementations 1 and 2, respectively).

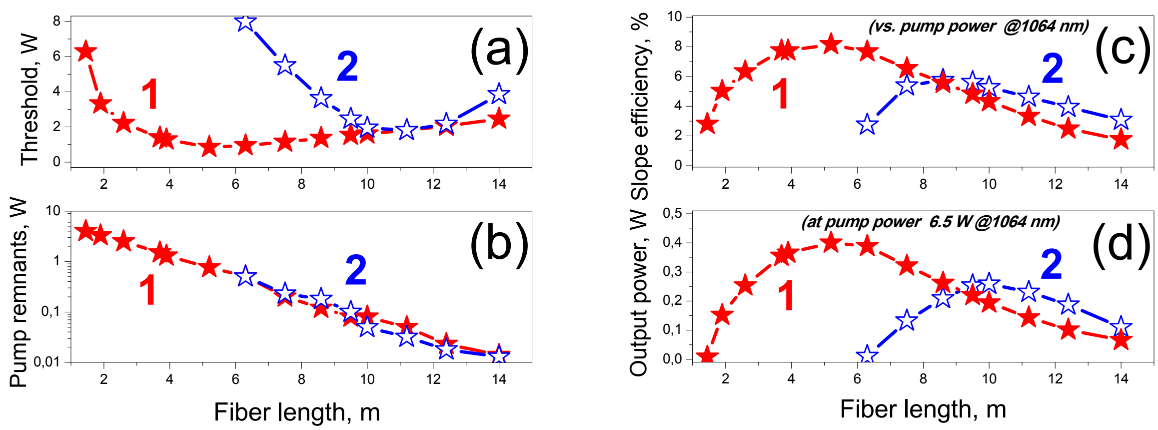


Figure 4. Output parameters of ~2.05-µm lasing vs. the YHDF length (L_{YHDF}): (a) threshold pump power; (b) 1.064-µm pump remnants (at P_P =6.5 W); (c) slope efficiency; (d) output power at P_P =6.5 W. Curves 1 (red) and 2 (blue) designate the data obtained for cavities 1 and 2, respectively.

The threshold pump power as low as ~0.8 W (see Fig. 4 (a)) and the output ~2.05-µm power and the slope efficiency as high as ~8.4% (when measured *vs.* pump power launched into the YHDF core) and >0.4 W, respectively (see Fig. 4 (c, d)), are the YHDFL's features, obtained using the current, non-optimized, laser design. Naming it non-optimized, we mean that, as seen *e.g.* from Fig. 4 (b), the best laser characteristics, referred above, are obtained when 1.064-µm pump remnants at the laser output are still noticeable (hundreds mW instead of desirable tens mW).

It is also seen from Fig. 4 that generally better performance of the YHDFL is obtained at using cavity 1 rather than cavity 2 – that is, lower threshold pump powers, bigger ~2.05-µm output powers, and higher slope efficiencies – are observed in the first case; compare the panels (a), (c), and (d) on the figure. This mostly stems from a higher Q-factor of cavity 1 (where the output coupler with higher reflectivity is used) and, thereafter, a less YHDF length (L_{YHDF} ≈5.0 m) necessitated for the 'optimal' operation (we imply here the laser operation optimal when the minimal threshold and the maximal output power and slope efficiency are attained). Furthermore, for cavity 2, where the more transparent at ~2.05-µm output coupler is employed, the optimal operation is accomplished for L_{YHDF} ≈10.5 m.

The existence of clearly expressed optimal YHDF lengths in these two circumstances is not surprising since a prerequisite for a fiber laser's optimal performance is optimal 'charge' of the active fiber by pump light. Indeed, there should be enough inversion stored in the active fiber, from one side (apparently, the part of inverted ions is proportional to active fiber's length) but, from the other side, there should be compromised impact of laser-light reabsorption by non-inverted ions (the effect also proportional to the active fiber's length). Hence, a compromise between the two trends establishes a length of the active fiber, providing the optimal laser performance, which is well illustrated by Fig. 4. In the meantime, notice the other important detail that considerably affects the YHDFL appearance, *viz.*, notable linear absorption at ~2.05 µm (γ_0 ~0.1 dB/m) inherent to silica fibers. Even at the 'optimal' conditions, revealed above for cavities 1 and 2 (L_{YHDF} ≈5.0 m and 10.5 m), this factor leads to $\gamma_0 \times L_{YHDF}$ ~1-dB or ~2-dB unavoidable loss.

Taking into account that 'cavity 1' (when using L_{YHDF} =5.0 m) provides in overall the best laser performance at the current stage of our work, we inspected it in more details; the results are given in Fig. 5.

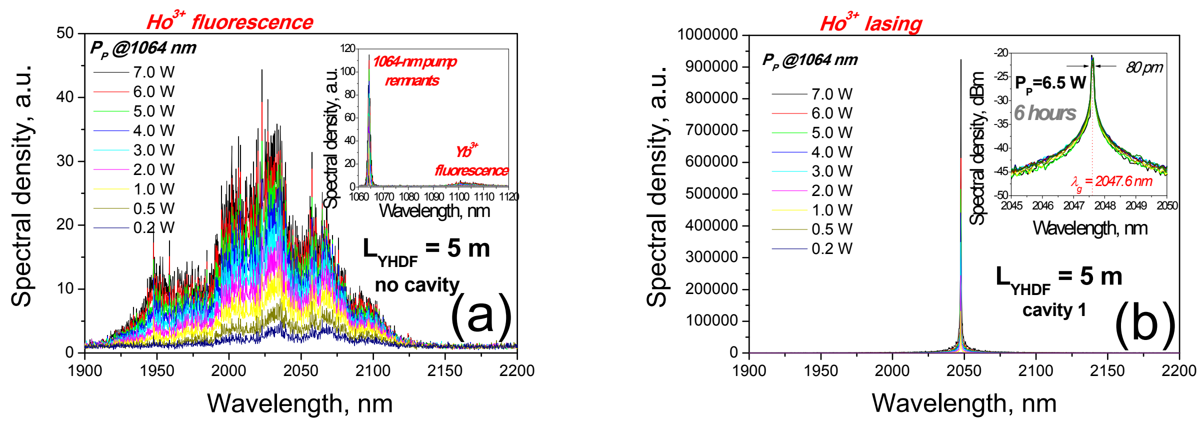


Figure 5. Optical spectra of (a) Ho^{3+} fluorescence (no cavity) and (b) ~2.05-µm lasing (cavity 1) obtained using the YHDF (L_{YHDF} = 5.0 m) at different pump powers, specified in the left-hand insets. The right-hand inset in (a) demonstrates the optical spectra nearby the pump wavelength (1060…1120 nm) and the right-hand inset in (b) shows long-term (6 hours) stability of the laser line (λ_g =2047.6 nm) at maximal launched pump power.

It is seen from comparison of main frames of Fig. 5 how, at given L_{YHDF} =5.0 m, ~2-µm fluorescence (Ho^{3+}) spectrum collapses to ~2.05-µm lasing, provided cavity 1 was arranged (*i.e.* FBGs 1 and 2 were spliced into the optical scheme); the data for various pumps P_p are shown by different-color curves in the figures. Then, from comparison of the Ho^{3+} fluorescence and lasing spectra it is seen that the generation wavelength, λ_g =2.045 µm would deserve optimization, *i.e.* tuning to higher values, say, to ~2.06…2.07 µm. Furthermore, as seen from the inset in Fig. 5 (a) (where we demonstrate the ~1-µm region of the output optical spectra, measured simultaneously with the ~2-µm one, depicted in the figure's main frame), only 1.064-µm pump remnants are pronounceable in the spectra, whilst Yb^{3+} emission (see the tiny fluorescence band nearby 1.1 µm) is vanishing in the system. We found necessary, for the case when the YHDF lased (see Fig. 5 (b)), to snapshot the laser line's behavior during a few hours of uninterrupted per-a-day work; the result of such test is exemplified by inset to Fig. 5 (b), when pump was kept at the maximum level. It was found that during ~6 hours of continuous operation the YHDFL's line (λ_g =2.0457 µm) was remarkably stable (spectrally and in amplitude); the latter seems to be an attractive property of the laser for applications.

In our opinion, the observations made from the analyses of the whole of the above data are in favor of the idea to pump an YHDF system 'off-resonance' the Yb^{3+} and Ho^{3+} co-dopants' absorption bands (*i.e.* at 1.064-µm wavelength). This measure seems to be relevant, given comparable small-signal absorption coefficients of Yb^{3+} at 1.064 μm and of Ho^{3+} in the spectrally adjacent ~1.15-μm band (refer to Fig. 1) and quite effective ET from the first to the latter ion, which both lead to effective homogeneous excitation of the YHDF through its length. In spite of the attractive properties of ~2-μm (Ho^{3+}) lasing demonstrated above, the chosen scheme certainly requires further exploration and optimization.

Regarding an optimization route to be undertaken, mention here the following steps. When using the current YHDF's design, these are: (a) searching for an optimal operation wavelength and reflection coefficients of FBG couplers, which would help in maximization of ~2-μm output power and slope efficiency whilst further minimization of the laser's threshold, and (b) tuning λ_P towards shorter wavelengths, which ought to lead to higher α_0–values (given by Yb^{3+} ions' absorption) and, hopefully, smaller L_{YHDF}–values, necessary for effective 'charging' of the Ho^{3+} subsystem, capable of lase (a decrease of intra-cavity fiber length is invaluable in virtue of high 'passive' loss inherent to silica glass, γ_0 ~0.1…0.2 dB/m at ~2.0…2.1 μm). Seemingly, one more measure to increase the laser efficiency is (c) spectral adjusting (by ~200 pm), by means of temperature control or mechanical tuning, of FBGs composing the YHDFL cavity (as seen from Fig. 2 (a), at the current implementation FBG1 and FBG2 are slightly spectrally misaligned). Our estimates show that slope efficiency of YHDF lasing can be increased up to ~15%. If such a laser can be used 'in-tandem' with a standard ~100-W 1.064-μm YDFL as a pump source, ~15 W at ~2-μm would be released.

However, a more relevant improvement of the current YHDF's design is to be done in terms of optimization of the volumetric Yb^{3+} / Ho^{3+} contains' ratio and also optimization of the co-dopants' absolute concentrations (subject to increasing). Unfortunately, an increase of Yb^{3+} concentration (remind, in the current YHDF's version it is ~6.0 wt.%, which results in >2000 dB/m absorption in Yb^{3+} 978-nm peak) is more than questionable because of an extremely undesirable photo-darkening effect[18]. [Fortunately, in the case of the YHDFL reported here, this effect was insignificant: See *e.g.* inset to Fig. 5 (b).] So, it is more constructive to increase Ho^{3+} concentration in YHDF at least twice (of course, this will be accompanied by a drop of the Yb^{3+}/Ho^{3+} volumetric ratio). Such an action would enhance the potential of Ho^{3+} ions as energy acceptors via the ET process and, at the same time, shorten optimal L_{YHDF}, which is desirable for effective 2-μm lasing, given the law of intra-cavity loss scaling ($\gamma_0 \times L_{YHDF}$).

4. CONCLUSIONS

We demonstrated, for the first time to the best of our knowledge, an YHDF-based all-fiber laser oscillating in CW at ~2.05 μm using an original pump scheme (a commercial 1.064-μm YDFL), implemented in the simplest Fabry-Perot cavity configuration. The ~2.05-μm YHDFL is shown to have a low (~0.8 W) threshold, moderate slope efficiency (~8.4%) and output power (~0.41 W at 6.5-W pump power launched into the YHDF core), and high spectral brightness of output (a laser line's spectrum was estimated to be ~70 pm within the whole pumps range). The YHDFL operation was tested in two cavity implementations, characterized by higher and lower Q-factors, and differences between the regimes given by the cavity's choice, were revealed. High stability of ~2.05-μm lasing (with fluctuations in output power of less than 3% during few hours per-a-day operation) ought to be noticed as an attractive feature of the system.

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