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Highly efficient, depressed-cladding thulium-doped fiber laser at 1762 nm

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A continuous-wave (CW) multi-Watt-level 1.76-µm all-fiber Tm-doped laser resonantly pumped at 1.56 µm is presented. To mitigate long-wavelength amplified spontaneous emission (ASE), an in-house-drawn depressed-cladding Tm-doped fiber (dc-TDF) was used as an active medium. In a linear cavity, an output power of 2.47 W, with an optical signal-to-noise ratio (SNR) exceeding 65 dB and a high slope efficiency of 81.3% relative to the launched power, was demonstrated. Furthermore, bidirectional pumping enabled output power scaling over 4 W with a slope efficiency of 69%. To our knowledge, this is the first demonstration of 1.7-µm laser operation using dc-TDFs.

In recent years, thulium-doped fiber lasers (TDFLs) operating at 1.7-µm wavelength have gained the attention of the research community, as they offer numerous advantages for various critical applications, notably in medical diagnostics (microscopy, biomedical imaging) [1,2], polymer processing [3], and trace gas detection [4]. However, laser operation at 1.7 µm in TDFLs presents significant technical challenges compared to the conventional 1.9–2 µm wavelength region. Low emission cross-section, strong reabsorption, and ASE-induced gain competition are the primary constraints on the development of efficient TDFLs operating at 1.7 µm [5]. To overcome these intrinsic challenges, a proper strategy for the laser system design must be applied. Key enabling technologies leading to the development of high-performance TDFLs include: (1) the use of strong core in-band pumping at wavelengths of ~1550–1600 nm, which makes it possible to use shorter pieces of Tm-doped fibers (TDFs) and hereby mitigating reabsorption effects and reducing the buildup of long-wavelength ASE [6,7]; (2) implementation of a low-Tm-doped-fibers results in enhanced fractional inversion and more effective thermal load distribution [7,8]; and (3) advanced ASE suppression methods in the 1.8–2 µm band including the utilization of passive wavelength-selective filters [9,10] or volume gratings and fiber Bragg gratings (FBGs) with highly wavelength-selective feedback [7,11]. These approaches have allowed significant performance improvements in short-wavelength TDFLs.

Recent demonstrations have established remarkable advancements in key performance indicators, including output power, slope efficiency, and optical SNR. In 2015, Daniel et al. [7] developed an all-fiber 1726-nm TDFL with a compression-tuned FBG, which emitted an output power of 12.6 W and a slope efficiency of 67% (63%) with respect to the absorbed (launched) power at 1565 nm. The optical SNR of the output was ~60 dB. In 2019, Burns et al. reported a record 47 W CW output power at 1726 nm using an in-house-fabricated fiber with only 0.2 wt% Tm^{3+} doping, also demonstrating a record slope efficiency of 80% versus absorbed 1580 nm pump power and a SNR of ~50 dB [8]. However, the laser was not in an all-fiber format. Zhang et al. demonstrated a resonantly pumped 1.72-µm TDFL in a ring cavity, providing an output power of 2.36 W with a slope efficiency of 50.2% determined with respect to absorbed pump power while maintaining >50 dB optical SNR [12]. The same group also reported on a 1720-nm TDFL intracavity-pumped by an Er/Yb-codoped fiber laser, achieving an output power of 1.13 W with a slope efficiency of 62.5% relative to the launched 1560-nm pump power and reaching a high SNR exceeding 65 dB [13]. Additionally, using commercially available single-mode TDF, bidirectionally pumped at 1570 nm, enabled the group to achieve a 5.92 W output at 1720 nm with a 64% slope efficiency versus the launched pump power, and an excellent output power stability with a root mean square (RMS) deviation of ~1.1% [14]. One can also find a detailed review of the recent progress of power scaling of 1.7-µm TDFLs in Ref. [15]. Despite the impressive results shown above, consecutive improvements in laser design are expected to yield even better output parameters. A notable example of these improvements is the use of a novel depressed-cladding thulium-doped fiber (dc-TDF) design with a characteristic W-shaped refractive index profile, acting as a distributed ASE filter that is tunable via the fiber bend radius [16-18].

In this Letter, we present, to the best of our knowledge, the first realization of a 1.7-µm fiber laser based on a dc-TDF. This approach allowed for efficient long-wavelength ASE suppression and demonstration of an output power of 2.47 W with a record slope efficiency of 81.3% (versus launched pump power), only slightly below the theoretical quantum efficiency limit (88.8%). Additionally, the effectiveness of a long-wavelength ASE suppression by coiling the dc-TDF into different shapes, as well as the power scaling of the laser up to 4 W using bidirectional pumping, were also presented.

The dc-TDF was drawn from a preform made in-house using the modified chemical vapor deposition (MCVD) technology combined with the ceramic nanoparticles doping method. In addition to aluminum oxide (Al_2O_3) and Tm^{3+} doping, the preform for the dc-TDF incorporated additional fluorine-doped layers. The dc-TDF (5 mol.% Al_2O_3, fluorescence lifetime ~603 µs) was specifically designed to effectively suppress ASE at longer wavelengths (>1800 nm) while shifting the gain toward shorter wavelengths (<1800 nm). The cutoff wavelength was engineered to be approximately 1850 nm, beyond which the fiber exhibits high propagation losses. The background losses were estimated using the standard cut-back method to approximately 41 dB/km at a wavelength of 918 nm. A depressed cladding with a refractive index depth (Δn_{dep}) of ~4.2×10^{-3} and a width (w_{dep}) of 5.9 µm was created around the core to achieve the targeted waveguiding properties. One (1D) and two-dimensional (2D) refractive index profiles (RIP) measured by an optical fiber analyzer (IFA-100, Interfiber Analysis Inc.) as well as a fiber end-face image are presented in Fig. 1.

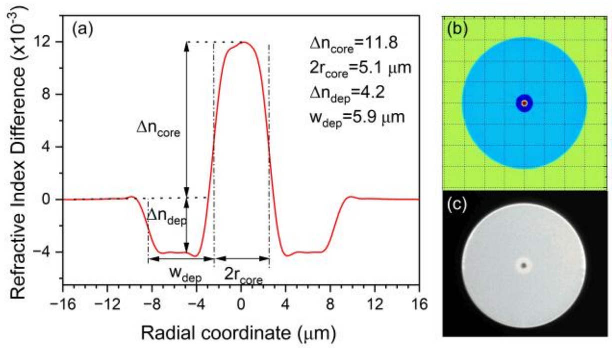

Fig. 1. 1D (a) and 2D (b) refractive index profile of the dc-TDF, microscope image of a fiber end-face (c).

The laser setup, arranged in a simple Fabry–Perot cavity, is depicted in Fig. 2. The dc-TDF, had a core diameter ($2r_{core}$) of 5.1 µm, 125-µm cladding, and Tm^{3+} concentration of ~1600 mol ppm (core absorption of 65 dB/m at 1640 nm). It was core-pumped via a fused 1560/1760 nm wavelength-division multiplexer (WDM) by an in-house-built erbium/ytterbium co-doped fiber laser (EYDFL1), delivering up to 3.75 W of CW radiation at a wavelength of 1565 nm. A polarization-insensitive fiber-optic isolator (ISO) was spliced to the EYDFL1 output to protect the pumped laser against any unwanted back-propagating pump radiation. The WDM was spliced between the output fiber port of the ISO and the passive fiber with a core/clad diameter of 10/130 µm and a section of highly reflective fiber Bragg grating (HR FBG) with a 3 dB reflection bandwidth of 1.06 nm at a center wavelength of 1762.13 nm, and a reflectivity of 99.87%. The laser cavity was formed using the HR FBG and a Fresnel reflection at the perpendicularly cleaved output end of the active fiber. For power scaling, the ISO and WDM were replaced with a fiber-optic circulator (CIRC) because the specified power-handling limit of the applied ISO was only 2 W. The entire dc-TDFL was placed on an aluminum water-cooled plate with the temperature set to 20ºC.

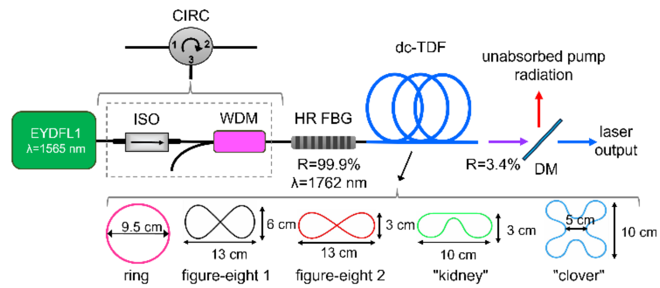

Fig. 2. Experimental setup of the Tm-doped fiber laser with schematically shown the various coiling shapes of the dc-TDF.

The W-type RIP enables bend-radius-dependent adjustment of the dc-TDF operating window into the 1.7–1.8 µm spectral band. However, to achieve efficient short wavelength laser generation the effective ASE suppression is necessary, but the losses introduced into the cavity must not be excessive. Therefore, we investigated coiling the dc-TDF into various shapes to analyze ASE suppression and laser efficiency. For this experiment, the 2.6 m-long dc-TDF was employed in the laser setup. All spectra were measured using an optical spectrum analyzer (Yokogawa, AQ6375), and the output power was measured using an optical power meter (Ophir, Laserstar) equipped with a thermal sensor (10A-V1.1). The results presented in Fig. 3 show that ASE suppression strongly depends on the coiling radius of the active fiber with poor suppression observed for dc-TDF coiled into the ring with radii greater than or equal to 9.5 cm. In this case, mostly ASE radiation was generated with a low slope efficiency of only 1.3% and no lasing was observed at the HR FBG's reflective wavelength (Fig. 3a, c).

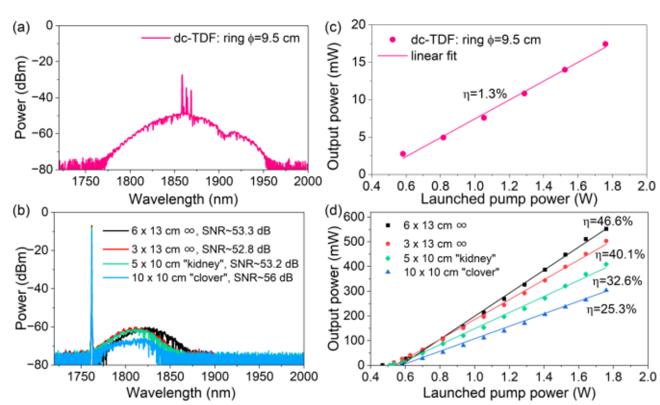

Fig. 3. Optical spectra (a, b) measured for various coiling shapes of the dc-TDF at the same pump power level of 1.52 W and the corresponding output power characteristics as a function of pump power (c, d).

However, coiling the dc-TDF into various shapes with varying the fiber bend radius yielded effective ASE suppression and enabled laser generation at 1762 nm (Fig. 3b, d). This is because the loss characteristic of the applied dc-TDF exhibits quasi-periodic variation, while the fiber bent radius is kept constant [17]. The best long-wavelength ASE suppression was achieved by coiling the dc-TDF into a "clover" shape with a 5 cm inner diameter. However, the highest slope efficiency of 46.6% was reached using a figure-eight active fiber shape with dimensions of ~6 x 13 cm (black trace in Fig. 3d). In all results presented in Fig. 3b, the ASE contribution to the total radiation was very small, not exceeding 0.5%. Consequently, the figure-eight 1 shape was selected for further power scaling of the TDFL.

Using the cut-back technique, the dc-TDF length was optimized at 1.53 m, yielding 0.89 W of output power for 1.54 W of launched pump power (Fig. 4). Shorter lengths of the dc-TDF reduced the output power, due to the lower total pump absorption and consequently lower gain. Conversely, the laser threshold increased monotonically from 223 mW to 543.5 mW with the active fiber length, owing to higher cavity loss.

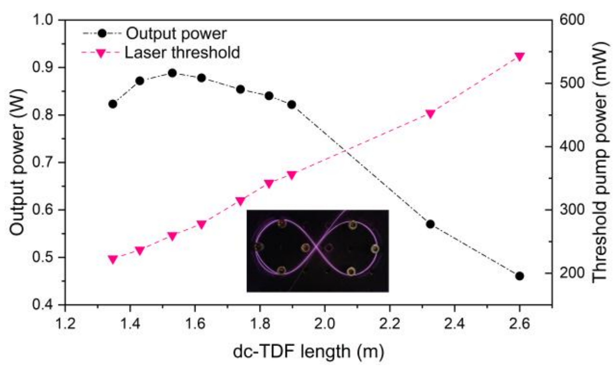

Fig. 4. Active fiber length optimization. Output power is measured at the same pump power of ~1.54 W; the dc-TDF is coiled into a 6x13 cm figure-eight shape (Inset: photo of the coiled dc-TDF).

For further power scaling WDM and ISO were replaced with the CIRC (Fig. 2), which also served as an optical isolator. The output power for the dc-TDFL versus launched pump power is plotted in Fig. 5. At the maximum pump power of ~3.33 W, the laser generated 2.47 W of CW output power when the optimal active fiber length was applied in the laser setup. For a 1.62 m-long dc-TDF, a record slope efficiency of 81.3% (determined with respect to the launched pump power) was obtained, whereas for other active fiber lengths in the 1.35-1.97 m range, the efficiency varied between 71.9% and 78.7%. To our knowledge, this is the highest reported values of the slope efficiency (relative to launched pump power) for 1.7 µm TDFLs, significantly exceeding the 62.5–64% range previously reported for all-fiber configurations [7, 13, 14]. The output spectrum was centered at 1762.7 nm and had a 3-dB bandwidth of ~70 pm. A residual ASE radiation appeared over 65 dB below the laser peak.

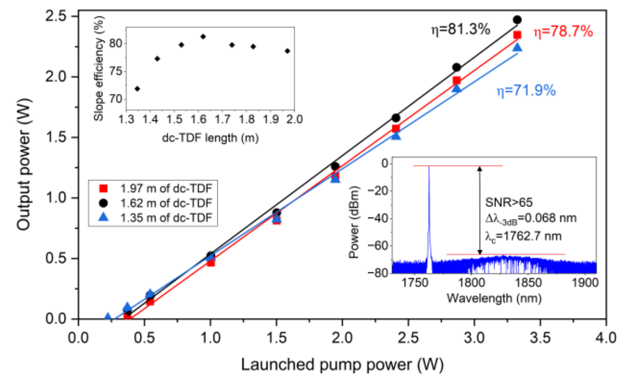

Fig. 5. Output power versus launched pump power for the laser setup with different dc-TDF lengths; upper inset shows a slope efficiency vs active fiber length, lower inset shows an optical spectrum measured with a resolution of 50 pm for the TDFL with 1.62 m of the active fiber and a maximum output power of 2.47 W.

It is worth noting that, during power scaling of the dc-TDFL, as the pump power increases, the ASE level remains constant, while all stored energy is efficiently generated at the 1762 nm laser wavelength. Consequently, the SNR in the optical spectrum rises from 5 dB at the lasing threshold (0.27 W of pump power) to over 65 dB at the maximum pump power of 3.33 W.

Because of the limited output power of EYDFL1, for further power scaling, we applied a bidirectional pump scheme, which is schematically shown in Fig. 6. Another, in-house-built erbium-ytterbium co-doped fiber laser (EYDFL 2) delivering up to 3.27 W of CW laser radiation at a wavelength of 1565 nm was used to pump an active fiber in a counter-propagating scheme. A fiber-optic circulator (CIRC 2) was used to monitor unabsorbed pump radiation while also ensuring optical isolation of EYDFL2. In this case, pump radiation was launched into the dc-TDF via a fused 1560/1760 nm WDM, whose signal port was cleaved perpendicularly to the fiber axis and served as an output coupler due to the ~3.4% Fresnel reflection.

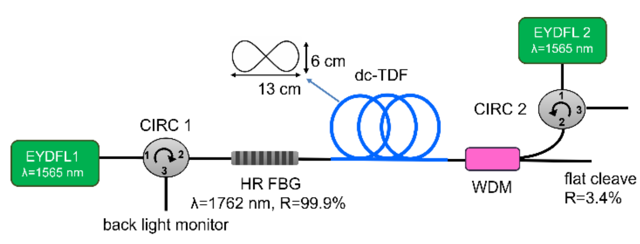

Fig. 6. Schematic of the bidirectionally pumped Tm-doped fiber laser.

The optimal length of the dc-TDF for this pump scheme was experimentally determined to be 1.8 m. The output power of the bidirectionally pumped dc-TDFL is plotted as a function of launched pump power in Fig. 7. At a maximum launched pump power of 6.25 W, we achieved 4.013 W of output power at a wavelength of 1762 nm with a slope efficiency of 69%. The reduced slope efficiency mainly resulted from additional losses introduced into the laser cavity by the WDM. Splice losses between the active fiber and passive components were typically low (on the order of a few tenths of a dB) and did not noticeably degrade laser performance. Since no power roll-off is observed in the output power characteristic, further power scaling should be possible in this laser setup. The inset in Fig. 7 shows the laser spectrum measured with 0.1 nm resolution at the maximum output power of over 4 W. The center wavelength was 1762.14 nm, and the 3-dB spectral bandwidth was 0.13 nm. The ASE radiation was observed ~63 dB below the laser peak, in the spectral region ranging from 1.76 to 1.87 µm. Despite the lower generation efficiency, Fig. 7 clearly shows that the properly coiled dc-TDF can effectively attenuate ASE at longer wavelengths even at higher output powers.

The results presented above demonstrate an attractive concept for efficient 1.7-µm wavelength laser generation from a TDFL using a properly designed dc-TDF with a high concentration of Tm^{3+} ions. This approach may serve as an alternative to the commonly used low-Tm-doped fibers in this wavelength range. A comprehensive comparison of key output parameters of 1.7-µm TDFLs, including the results presented herein, is summarized in Table 1.

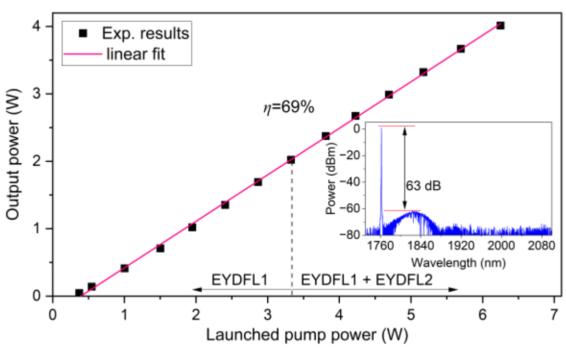

Fig. 7. Output power versus launched pump power for the bidirectionally pumped TDFL. Inset presents the optical spectrum measured at the maximum output power of 4.013 W.

Table 1. Performance comparison of 1.7 µm CW TDFLs

Output power (W)	TDF (Tm^{3+} concentration)	Slope eff.[a] (%)	SNR (dB)	Ref.
12.6	0.2 wt.%	63 (67)	60[b]	7
47	0.2 wt. %	- (80)	50[b]	8
1.13	0.3 wt. %	62.5 (68)	65	13
5.92	0.3 wt. %	64	66	14
2.47	0.45 wt %	81.3	65	This work
4	0.45 wt %	69	63	This work

[a] Slope efficiency with respect to the launched (absorbed) pump power.
[b] Values read out from a graph.

In summary, we present the first Tm-doped all-fiber laser operating in the 1.7–1.8 µm spectral range, utilizing a novel depressed-cladding active fiber. In the co-propagating pumping scheme, a maximum output power of 2.47 W was generated with a slope efficiency of 81.3% (close to the theoretical Stokes limit 88.8%) using a 1.62 m of dc-TDF bent in the 6 x 13 cm shape of a figure-eight. To the best of our knowledge, the achieved slope efficiency is the highest one reported for short-wavelength TDFLs. The laser operated at 1762 nm, with a 3-dB linewidth of ~68 pm and a SNR exceeding 65 dB. In addition, using the bidirectional pump scheme allowed achieving an output power exceeding 4 W with a slope efficiency of 69%. This approach has high potential for further power scaling.

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Disclosures. The authors declare no conflicts of interest.

Data Availability Statement (DAS). Data underlying the results presented in this paper are available in Ref.[19].

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