



# All-fiber core-pumped Ho-doped laser with 95 W output power and high efficiency

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**Abstract:** We report a core-pumped, all-fiber, monolithic holmium-doped silica fiber laser (HDFL) pumped at 1940 nm by a high-power Tm-doped fiber laser. The system delivers up to 95 W of continuous-wave output power at 2109 nm, representing one of the highest reported powers for a core-pumped holmium fiber laser. A slope efficiency of 84% with respect to launched pump power is achieved, making a 10% improvement over previously published papers. These results confirm the effectiveness of core pumping using advanced Tm-doped fiber architectures and highlight the potential of compact, efficient Ho-doped fiber sources for high-power applications in the 2.1  $\mu\text{m}$  spectral region. All experiments were further supported by numerical modelling together with a simulation of possible further power-scaling up to 250 W.

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## 1. Introduction

Laser sources operating within the 2  $\mu\text{m}$  spectral band have gained significant interest owing to their broad applicability in fields such as materials processing, medicine, defence, and the generation of mid-infrared (mid-IR) radiation through non-linear frequency conversion [1,2]. In particular, applications that depend on free-space beam propagation, including LIDAR, remote sensing, free-space optical communication, and directed-energy technologies, stand to benefit from high-power laser systems emitting in the 2.1 – 2.2  $\mu\text{m}$  range, where atmospheric transmission is especially favourable [3,4].

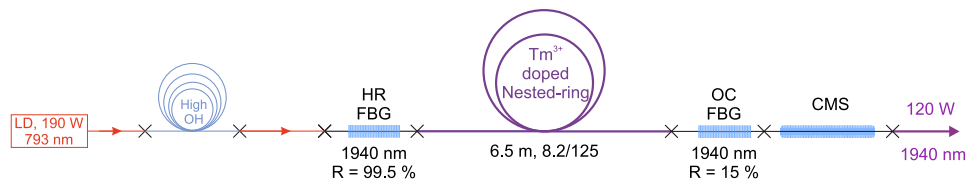
Ho-doped silica fibers have a broad absorption band with its maximum located at 1950 nm [5,6], which makes them ideal for pumping by Tm-doped fiber lasers that can be efficiently operated at this wavelength. This resonant pumping scheme allows for a low theoretical quantum defect of < 8 % arising from the pump/signal photon energy difference, which is preferable for high-power operation as the residual heat can be effectively handled and dissipated even in core-pumped systems [6]. Contrary to cladding-pumped Ho-doped lasers, which require a complex 'all-glass' triple-clad fiber design [2–4,7] due to the high pump absorption in the polymer coating of typical double-clad fibers, the core-pumped approach allows the use of a simple single-clad fiber [5,6]. The in-band core-pumped laser architecture is limited in power scaling, due to both the dependence on the power scalability of the pump laser and to the thermal constraints imposed by confining high intensities within the small core area. On the other hand, this design enables the extraction of 100-W-class output powers from active fibers with small cores of around 10  $\mu\text{m}$ , and achieves significantly higher efficiency (by > 20 %) compared with cladding-pumped systems, owing to the shorter fiber lengths required [5,6]. Typical cladding-pumped holmium lasers

exhibit an efficiency in the range of 50 – 60 % [2,7], whereas core-pumped Ho lasers exceed 80 % and have been shown to reach up to 87 % for low power (6 W) lasers [8].

This paper reports a core-pumped, all-fiber, monolithic holmium fiber laser pumped by a Tm-doped fiber pump system. The results demonstrate a continuous-wave output power of up to 95 W with a slope efficiency of up to 84 % at 2109 nm. These results represent a 10 % increase in slope efficiency compared with the only previous report of a core-pumped laser achieving similar output power [6], and an additional 25 W increase in output power, permitted by the use of improved FBGs with higher core-power handling capability and better thermal management, compared with the conference talk given at ASSL 2025 [9].

## 2. Experimental details

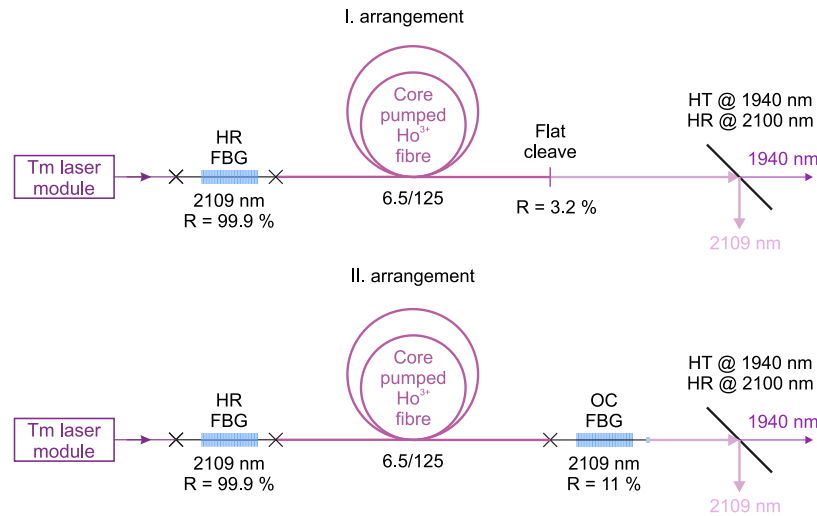
The whole laser setup consisted of an in-house built Tm-doped fiber laser (TDFL) emitting at 1940 nm used as a resonant pump source for a single-clad Ho-doped silica fiber. The 1940 nm pump wavelength was chosen due to the availability of fiber components. In Fig. 1 there is TDFL that was designed as a monolithic, all-fiber configuration to maintain simplicity. An nLight (element e24i) laser diode (190 W @ 793 nm, 200/220  $\mu\text{m}$ , NA 0.22) was used as the pump source for the TDFL, with its pigtail spliced to a 12 m coil of high-OH fiber (Thorlabs, FG200UEA) to prevent damage from parasitic back-scattered 2  $\mu\text{m}$  radiation. The high-OH fiber was tapered down to a 125  $\mu\text{m}$  cladding diameter to match the pigtail of the highly reflective fiber Bragg grating (HR FBG) (10/125  $\mu\text{m}$ ,  $R > 99.5\%$  @ 1940 nm, bandwidth 1.5 nm at  $-3$  dB). The HR FBG was spliced to a 6.5 m length of the nested-ring active fiber (in-house fabricated in the ORC laboratory) [10,11] with the following specifications: Tm<sup>3+</sup> concentration 4 wt. % (15,000 mol ppm), core diameter 8.2  $\mu\text{m}$  (NA = 0.15), and an octagonal cladding with dimensions 122  $\mu\text{m}$  (flat-to-flat) and 132  $\mu\text{m}$  (corner-to-corner), with a cladding NA of 0.46. The output side of the cavity was spliced to an output coupler (OC) FBG (10/125  $\mu\text{m}$ ,  $R = 15\%$  @ 1940 nm, bandwidth 0.42 nm at  $-3$  dB). A cladding-mode stripper (CMS) was spliced to the output pigtail of the OC FBG to remove any residual pump light at 793 nm. The maximum output power of this pump laser was 120 W, with the possibility of reaching up to 130 W by overdriving the pump diode for short periods [9].



**Fig. 1.** Layout of Tm-doped fiber laser used as pump source for HDFL.

The output pigtail of the CMS was spliced into the HDFL setup, which was implemented in two arrangements, as shown in Fig. 2. Two different active Ho-doped fibers were fabricated, in-house at the Institute of Photonics and Electronics (IPE), and tested. The laser cavity in I. arrangement used the 3.2 % Fresnel reflection from the perpendicularly cleaved end of the HDF as the output coupler. Arrangement II, on the other hand, employed an OC FBG with  $R = 11\%$  at 2109 nm (bandwidth 0.5 nm at 3 dB). The HR FBG was identical in both configurations, providing 99.9 % reflectivity at 2109 nm (bandwidth 1.5 nm at 3 dB). Both FBGs have 1.5 m long pigtails based on Coherent SM-GDF-10/130-15M fiber with 10  $\mu\text{m}$  (0.15 NA) core and 130  $\mu\text{m}$  cladding diameter.

The active fibers were prepared using the modified chemical vapour deposition (MCVD) method in combination with nanoparticle doping, further details in [12]. Both fibers were coated with a high-index polymer, and further details are summarised in Table 1. The optimal lengths of



**Fig. 2.** Layout of core-pumped HDFL illustrating two used arrangements – I. with flat cleave and II. with FBG as output coupler terminated by endcap.

active fibers were determined based on the laser cut-back measurements. The launched pump power was measured after the HR FBG pigtail and does not include any correction for the splice loss between the passive FBG pigtail and the active Ho-doped fiber. The output power and unabsorbed pump power were separated using a dichroic mirror (Layertec, HR @ 2.1  $\mu\text{m}$ , HT @ 1.94  $\mu\text{m}$ ) and measured using two detectors (Gentec UP19K-110F-H5-D0). It is worth noting that for both fibers the unabsorbed pump power at maximum pump was < 700 mW. The active fibers and the FBGs were attached to a water-cooled aluminium cold plate and maintained at 15 °C.

**Table 1.** Details of tested Ho-doped active fibers;  $\tau_{up}$  – fluorescence decay time of upper laser level  $^5I_7$ .

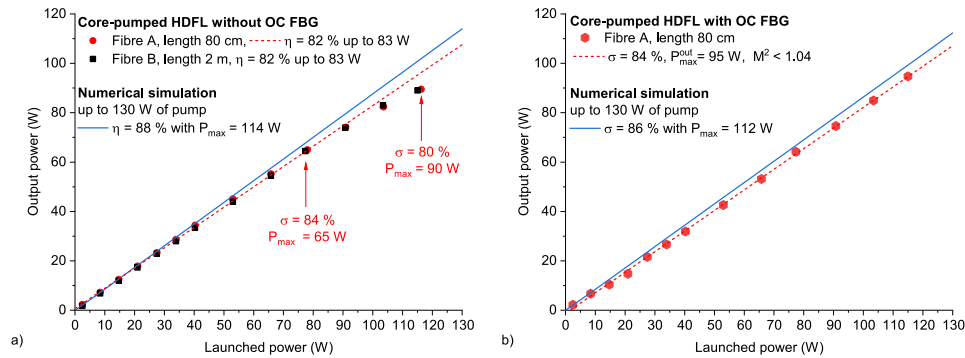
Fiber	Ho <sup>3+</sup> (mol ppm)	Al <sub>2</sub> O <sub>3</sub> (mol %)	Fiber length (m)	Core/Cladding ( $\mu\text{m}$ )	Core absorption (dB/m @ 1950 nm)	$\tau_{up}$ (ms)
A	3850	9.4	0.8	6.5/125	108	1.3
B	1300	10.4	2	5.9/125	35	1.6

Laser emission wavelengths were measured at corresponding maximum output powers, using an optical spectral analyser (OSA) Yokogawa AQ6375 (resolution 0.05 nm). The laser beam spatial profile was measured at a power level of 20 W for an attenuated collimated beam by the Spiricon Pyrocam IIIHR (pixel size 75  $\mu\text{m}$ , active area 12.8  $\times$  12.8 mm). The  $M^2$  measurements were carried on by a Nanoscan NS2s-PYRO (slit 5  $\mu\text{m}$ ) mounted on a rail.

### 3. Results and discussion

In previous publications [5,13], a numerical model of Ho-doped fiber lasers was introduced to simulate and predict the behaviour of the laser system. These frameworks [5,13] were used to evaluate the output characteristics of tested Ho-doped fibers, and the results of these simulations are presented in Fig. 3 together with experimental data, showing good agreement overall. The discrepancies between simulation and experiment, mainly at high-powers, may be attributed to thermal effects, which are not accounted for in the model.

Ho-doped active fibers were first tested in the I. arrangement without an OC FBG in order to evaluate optimal fiber length, output power characteristics, optimise cooling, and inspect the



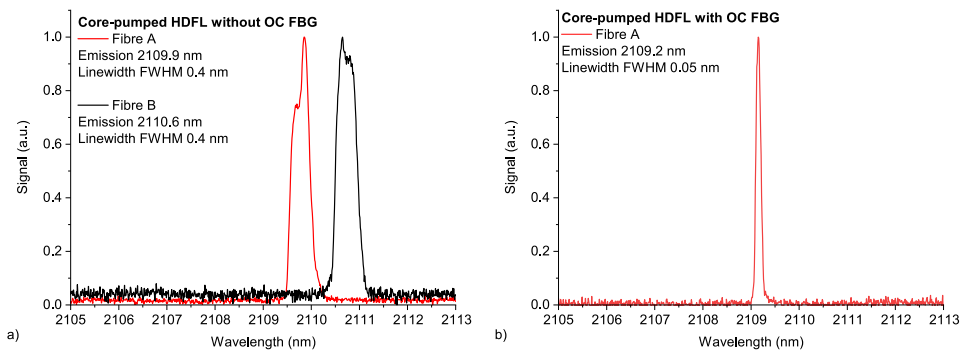
**Fig. 3.** Laser characterization for HDFL cavity with (a) flat cleave and (b) FBG output couplers together with numerical simulation results;  $\eta$  - slope efficiency,  $P_{max}$  - maximum reached output power.

output beam profile. Fibers A and B were tested up to the maximum available pump power, and their output characteristics are presented in Fig. 3(a), exhibiting similar behaviour. The output power up to 65 W shows a slope efficiency of 84 % with respect to launched pump power. Above 65 W, a slight roll-off can be observed, reducing the slope to 82 % up to 83 W. This roll-off originates from thermal issues at the output fiber tip. As the output coupler was formed by a flat cleave, a portion of the back reflection was likely scattered outside the core area and began heating the polymer coating, this was observed by a thermal imaging camera. As a result, at maximum pump power the slope efficiency further decreased to 80 %, and the maximum output power reached 90 W. The primary cause of the reduced output power and slope efficiency arises from thermal effects. In Ho-doped fiber lasers, heat is generated primarily through quantum-defect heating, non-radiative relaxation and background absorption. As the pump power increases, the resulting temperature rise leads to changes in the emission and absorption cross-sections, a reduction in the upper-state lifetime and increased reabsorption due to the quasi-three-level nature of the Ho transition. Due to the refined fiber composition and fabrication, both active fibers, despite having different  $\text{Ho}^{3+}$  and  $\text{Al}_2\text{O}_3$  concentrations, exhibited similar laser performance, even though their optimal fiber lengths differed by a factor of 2.5. The results for both fibers are therefore very similar, as shown in Fig. 3(a)). The numerical simulation predicts a maximum output power of 105 W with a slope of 88 %, but this deviation from experiment is likely due to thermal effects, as up to 65 W, the simulations and measurements show much closer agreement. The numerical simulation assumes temperature-independent spectroscopic parameters and neglects distributed thermal gradients, hence it overestimates the achievable slope efficiency at high power. As the simulated results are almost identical for both Fiber A and Fiber B, only the results for Fiber A are presented in Fig. 3(b)).

Further experiments incorporating an FBG as the output coupler were carried out with both fibers A and B. However, due to the mismatch between the core diameter of fiber B and the passive fibers used as pigtailed for the FBGs, this led to modal mismatch, which introduced additional losses in the cavity. Consequently, the monolithic laser setup with fiber B did not allow efficient operation. It is worth noting that this issue could be resolved by fabricating a new fiber with modified core dimensions, as previous laser experiments, Fig. 3(a)), indicate that this fiber can deliver high output powers and high efficiency. On the other hand, fiber A has better modal-match and therefore allows to build and operate the laser in a monolithic cavity design. The results are shown in Fig. 3(b)) together with the numerical simulation. The OC FBG pigtail was terminated with an endcap to protect the fiber from potential laser-fusing effects arising from the high power density. This also helps to prevent parasitic back-reflections into the polymer

coating. No overheating of the output fiber tip was observed in this configuration, and the output power remained stable up to the full pump power of the Tm-fiber laser. A maximum output power of 95 W with a slope efficiency of 84 % was achieved, comparable to the 88 % slope predicted by the numerical model. Ultimately, these experiments were limited by the performance of the thulium pump laser source and fiber components, which were driven beyond their datasheet specifications. Although the residual unabsorbed pump power was separated in free space, its level remained relatively low ( $< 0.7$  W) for both fibers. As this is a core-pumped system, a cladding-mode stripper cannot be used to remove residual pump light. The only practical all-fiber solution is therefore to extend the length of the active fiber to absorb the remaining pump light. This would still yield an efficiency an efficiency exceeding 80 %.

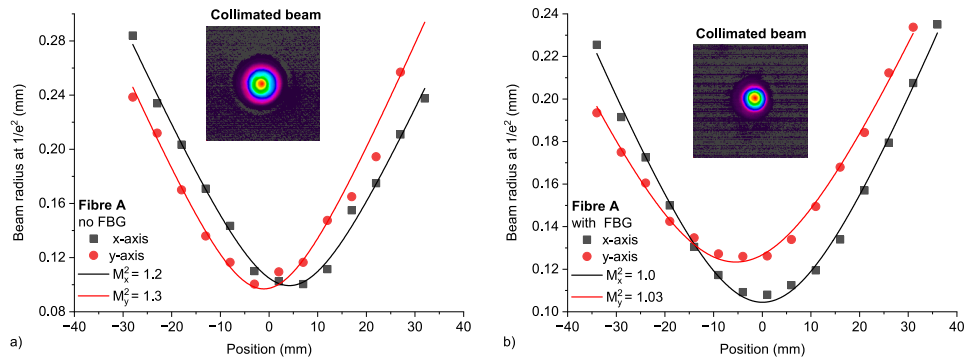
The emission spectra were measured for both arrangements. As seen in Fig. 4, without the OC FBG the emission lines were significantly broader, as they were not stabilised by the second FBG. The FWHM values were 0.4 nm with a maximum at 2109.9 nm for fiber A, and 0.5 nm with a maximum at 2110.6 nm for fiber B. In contrast, Fig. 4(b) shows the emission line for the laser cavity with an OC FBG, which is noticeably narrower, peaking at 2109.2 nm with FWHM  $< 0.1$  nm.



**Fig. 4.** Laser emission wavelength for HDFL cavity with (a) flat cleave and (b) FBG output coupler.

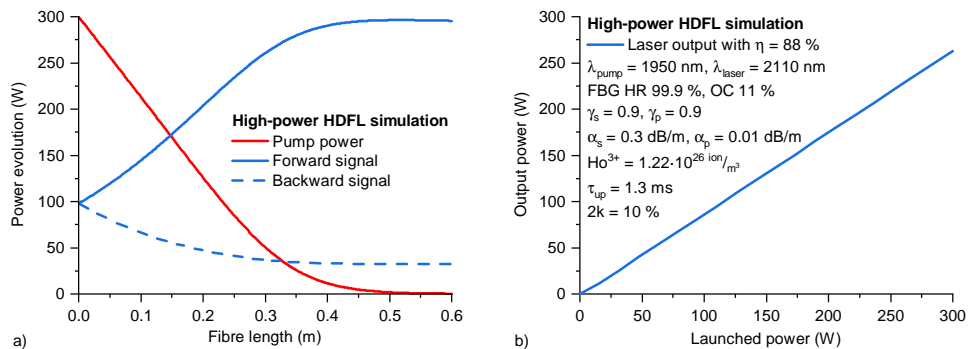
The beam quality of the laser was measured for both configurations. The  $M^2$  measurements, shown in Fig. 5 together with images of the collimated beams as insets, indicate that the  $M^2$  values for the laser without an OC FBG were 1.2 and 1.3 in the  $x$ - and  $y$ -axes, respectively. The beam quality was improved to  $M_x^2 = 1.0$  and  $M_y^2 = 1.03$  for the complete laser cavity, with the OC FBG and its pigtail terminated with an end-cap. The presented  $M^2$  measurements are for Fiber A only, as they allow a direct comparison between the configurations with and without the OC FBG. The beam quality of Fiber B was measured only in the configuration without the OC FBG, yielding  $M_x^2 < 1.2$  and  $M_y^2 < 1.1$ .

Further power scaling with the same fiber does not seem feasible, as we were already at the limit of the pump Tm laser source and were approaching the thermal limits of the holmium laser and exceeding limits of fiber components. A possible route for further power scaling of core-pumped systems could involve increasing the core size of the Ho-doped active fiber together with the use of an LMA-based thulium pump source with core/cladding sizes of 25/400  $\mu\text{m}$ . This should allow power scaling to the range of 250 W at 2.1  $\mu\text{m}$ , provided the slope efficiency  $> 80$  %. As a representative example, shown in Fig. 6, we run a numerical simulation of a fiber laser employing an holmium active fiber with a 25  $\mu\text{m}$  core diameter and a maximum pump power of 300 W at 1950 nm, yielding up to 263 W with a slope efficiency of 88 %. The simulations were based on the theory presented in [13], using the framework previously published in [5], and employed the same fiber composition as Fiber A, but with a scaled core size. The maximum



**Fig. 5.** Beam quality,  $M^2$ , results for HDFL with (a) flat cleave and (b) FBG output couplers for fiber A.

pump power for this calculation was chosen to match power handling specification of commercial 25/400 FBGs and also a thermal load comparable to the experiments and results presented above, ensuring that thermal management is feasible.



**Fig. 6.** Numerical simulation for further power-scaling of core-pumped holmium fiber lasers (a) power evolution along the fiber length, (b) output laser characteristic;  $\eta$  – slope efficiency,  $\gamma_s$  and  $\gamma_p$  – signal and pump overlap,  $\alpha_s$  and  $\alpha_p$  – core loss of signal and pump,  $\tau_{up}$  – upper laser lifetime,  $2k$  – percentage of holmium pairs.

Any further increase in power would require an all-glass, triple-clad Ho-doped fiber, along with cladding pumping, to effectively dissipate the heat load. However, the main limitation remains the power scaling of Tm laser sources, which have been restricted to about 1 kW of output power due to thermal constraints for more than the past decade [14,15].

#### 4. Conclusion

An in-band core-pumped Ho-based fiber laser utilising two different active fibers were presented with up-to date highest slope efficiencies of up to 84 % with respect to launched power for any lasers exceeding 30 W. Based on previous published research [6] this is an increase in efficiency by 10 % with similar output power of 95 W. Two active fibers with different compositions were tested and produced almost identical laser results in a 99 – 4 % laser setup. This shows that even with a lower doping level and a longer active fiber, it is still possible to achieve high power, which could be beneficial for further power scaling and laser development. Moreover, both setups, using a flat-cleave output coupler and an FBG, make it possible to achieve good beam quality. As mentioned above, further power scaling would be possible under several changes

such as increasing core size or introducing cladding pumping. The former one was elaborated and simulated in discussion showing prospect of reaching  $> 250$  W of output power with slope exceeding 80 %. The latter approach would result in higher output powers, but with a decrease in efficiency down to approximately 60 %, as shown in [2,7], unless the fibers are tailored to reduce core propagation loss. The results present in this work shows prospect of reaching high efficiency and high-power systems with core pumping setup.

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**Disclosures.** The authors declare no conflicts of interest.

**Data availability.** Data underlying the results presented in this paper are available online at [16].

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