

# Tunable Holmium-doped Fiber Laser with Multi-watt Operation from 2025 nm to 2200 nm

LARS G. HOLMEN<sup>1,2,3,\*</sup>, PETER C. SHARDLOW<sup>1</sup>, PRANABESH BARUA<sup>1</sup>, JAYANTA K. SAHU<sup>1</sup>, NIKITA SIMAKOV<sup>4</sup>, ALEXANDER HEMMING<sup>4</sup>, AND W. ANDREW CLARKSON<sup>1</sup>

<sup>1</sup>Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK

<sup>2</sup>Norwegian Defence Research Establishment (FFI), Kjeller, NO-2027, Norway

<sup>3</sup>Department of Technology Systems, University of Oslo, Kjeller, NO-2027, Norway

<sup>4</sup>Directed Energy Technologies and Effects, WCD, Defence Science and Technology, Edinburgh, SA 5111, Australia

\* Corresponding author: Lars.Holmen@ffi.no

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The emission band of holmium-doped silica fibers extends beyond 2200 nm, which means these lasers have potential of covering considerable parts of the atmospheric transmission window between  $\sim 2100$  nm and 2250 nm. However, efficient operation towards 2200 nm is challenging due to absorption in fused silica at the laser wavelength. Here we present a holmium-doped fiber laser specifically targeting long wavelength operation. The laser is implemented as a high-feedback wavelength selective ring cavity, and is tunable from 2025 nm to 2200 nm. A maximum slope efficiency of 58 % is obtained at 2050 nm, and a slope of 27 % at 2200 nm. A power of 5.5 W from a single aperture (8.9 W total) is demonstrated at 2200 nm. Our results represent extended coverage of the 2  $\mu$ m spectral band with multi-watt-level silica fiber lasers. © 2019 Optical Society of America

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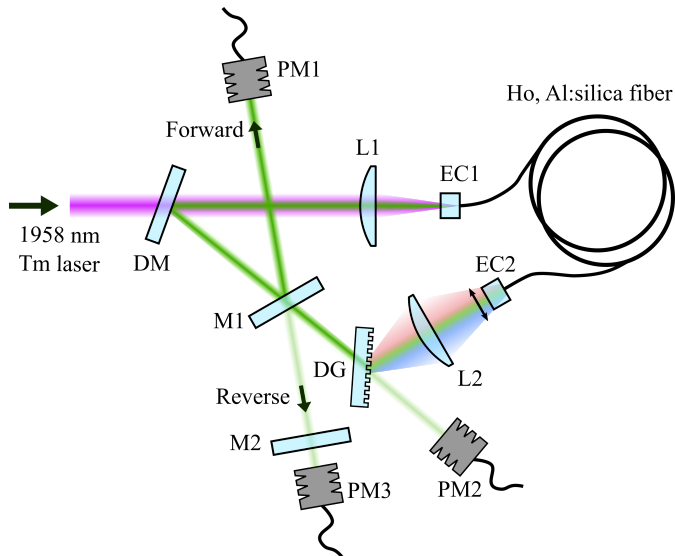
High power laser sources in the 2  $\mu$ m spectral region are of great interest in a wide range of fields covering material processing, medicine, defense, and mid-IR generation through frequency conversion [1]. Lasers operating in the atmospheric transmission window between 2100 nm and 2250 nm are particularly attractive in applications involving free-space beam propagation such as lidar and remote sensing, free-space communications and directed energy systems. Eye safety is an additional vital consideration in such applications, and 2  $\mu$ m emission is strongly preferred over more conventional 1  $\mu$ m-sources.

Both thulium and holmium doped silica fiber lasers emit in the 2  $\mu$ m-band. Thulium fiber lasers provide excellent performance around 2  $\mu$ m, but efficient operation above  $\sim 2100$  nm is challenging [2, 3]. Operation of thulium lasers at 2198 nm has been demonstrated using a high feedback cavity, with reports of slope efficiencies of 17 % and modest power levels of 550 mW [4]. In comparison, Ho lasers provide extended coverage into the atmospheric transmission window due to a slightly red-shifted emission peak that reduces issues with parasitic operation when tuned to longer wavelengths. For instance, high power opera-

tion of a Ho fiber laser tunable from 2040 nm to 2170 nm with reasonable efficiency has previously been demonstrated [5].

Ultimately, the limiting factor for long wavelength operation of rare earth doped fiber lasers is the diminishing emission cross section and competition from gain in the “natural” operating region, leading to dominating amounts of amplified spontaneous emission (ASE) and parasitic lasing. Different strategies have been explored to facilitate laser emission at longer wavelengths. Firstly, filtering techniques can be used, where additional losses are introduced at short wavelengths. This can be achieved by using e.g. photonic band gap technology [6], or by heating the quasi three-level gain medium to enhance reabsorption [7]. Secondly, inversion management has been shown to provide extended operation by limiting the gain at short wavelengths. By pumping resonantly at long wavelengths, the excitation can be distributed over a long fiber, whereby the gain spectrum is red-shifted since the maximum inversion is lowered [7, 8]. Finally, long-wavelength operation can be achieved using high Q cavities with selective feedback to obtain sufficient gain, although this is inevitably associated with reduced efficiency.

Operation of holmium silica fiber lasers towards 2.2  $\mu$ m presents challenges due to the reduced emission cross section, but also increasing propagation losses associated with the multiphonon absorption edge of the host material. Another major source of loss in this spectral regime is caused by the  $\nu_3 + \nu_1$  vibrational combination mode of bound hydroxyl (SiOH) [9]. Loss from OH<sup>-</sup>-contamination can be significant in the entire 2  $\mu$ m-band, but is particularly detrimental around 2.2  $\mu$ m where the absorption peaks. This puts stringent requirements on fiber fabrication to minimise OH<sup>-</sup>-inclusion, and concentrations below the ppm-level are essential [5]. The unavoidable propagation losses at the long-wavelength edge of holmium-doped silica exclude the approach of inversion management by increasing the fiber length and pumping in-band at increasingly long wavelengths [7]. Instead of gain suppression at short wavelengths, high feedback with strong wavelength selectivity becomes necessary for stable long-wavelength operation. Previous studies have shown Ho fiber lasers operating out to 2210 nm [10], however an extremely high Q-cavity configuration with highly reflective fiber Bragg gratings on both ends was required for



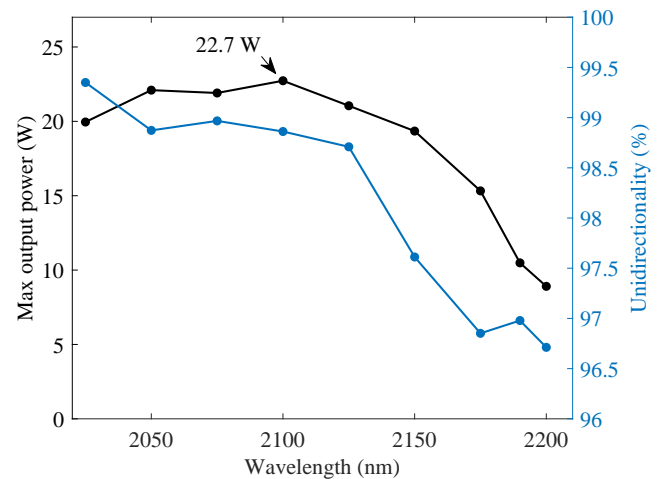
**Fig. 1.** Schematic of the tunable Ho-doped fiber laser, containing a dichroic mirror (DM), mirrors (M), diffraction grating (DG), power meters (PM), end caps (EC) and lenses (L). The laser oscillates in the counterclockwise direction.

suppressing shorter wavelength parasitic lasing. This limited the slope efficiency to 4 % and the power to 140 mW.

In this Letter, we investigate the limits of long-wavelength tuning of a holmium-doped fiber laser, and report for the first time, to the best of our knowledge, watt-level output from a silica fiber laser operating beyond 2.2  $\mu\text{m}$ . A tunable ring-oscillator was built and optimized for long-wavelength operation, where the ring cavity avoids double-pass ASE and reduces propagation losses through single-pass amplification. High wavelength selective feedback from a transmission diffraction grating allowed continuous tuning and stable laser operation from 2025 nm to 2200 nm, with a maximum output power of 22.7 W obtained at 2100 nm and 8.9 W at 2200 nm. With a laser slope efficiency of 27 % demonstrated at 2200 nm, considerable power scaling of fiber laser sources in this spectral regime is seen to be viable.

The laser setup is illustrated in Figure 1. Light from a Tm-doped fiber laser was free-space launched through a dichroic mirror (HR from 2050–2200 nm, HT at 1958 nm) into the core of a 6.5 m long Ho-doped fiber (core diameter 14  $\mu\text{m}$ , numerical aperture 0.12). The Tm pump laser was cladding-pumped with a 790 nm diode laser and was capable of delivering >60 W from a single-mode fiber. A fiber Bragg grating locked the pump wavelength to 1958 nm, and the laser had a linewidth below 0.1 nm. The in-house fabricated Ho fiber had a small signal absorption of 35 dB/m at 1950 nm, and extremely low levels of  $\text{OH}^-$ -contamination below 0.1 ppm both in the core and the cladding [11]. The fiber had an all-glass triple clad design suitable for resonant 2  $\mu\text{m}$  cladding pumping, in which configuration slope efficiencies up to 70 % with respect to absorbed pump power have been demonstrated [11]. The pure silica inner cladding of this fiber had a 65  $\mu\text{m}$  octagonal cladding (flat-to-flat), which was overjacketed with 180  $\mu\text{m}$  of low-index fluorine-doped silica.

Both ends of the gain fiber were  $\text{CO}_2$ -laser-bonded to anti reflection-coated (AR) end caps to suppress broadband feedback and parasitic lasing. An intra-cavity fused silica transmission grating (560 lines/mm) in Littrow configuration provided wave-

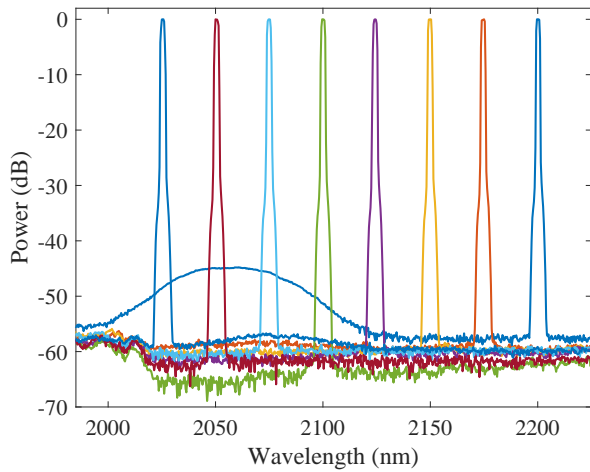


**Fig. 2.** Maximum output power (black) and the degree of unidirectionality (blue) measured at different wavelengths. The pump laser power was 42 W.

length selective feedback with the first diffracted order fed into the other end of the fiber to form a tunable ring cavity. The angular dispersion introduced by the grating was converted to a spatial chirp of wavelengths in the focal plane of lens L2. Tuning was achieved by translating the fiber end in this plane, as indicated by the arrow in Figure 1. For large wavelength shifts, L2 was also translated to avoid coupling losses from off-axis beam propagation. The lenses used were Infrasil<sup>®</sup> triplets with a 25 mm focal length, and were positioned to obtain a collimated beam in the tuning cavity with a measured  $D4\sigma$  beam diameter of 4.4 mm. Outcoupling was achieved with mirror M1, which had a reflectance of 20 % on one side and an AR-coating on the other. Unidirectional operation was forced by retro-reflecting reverse output arm from M1 [12, 13], and the fraction of light circulating in the wrong direction was determined from the power transmitted through M2 ( $R = 60\%$ ). Unabsorbed pump light is for clarity not shown in the schematic, but was measured on a separate power meter. Optical spectra were measured with an optical spectrum analyzer (Yokogawa AQ6375), a pyroelectric array (Spiricon Pyrocam III) was used for beam imaging and a scanning slit beam profiler (Ophir NanoScan 2s Pyro) for measuring the  $M^2$  beam quality.

Figure 2 shows the maximum output power when tuning from 2025 nm to 2200 nm for a pump laser power of 42 W. The highest power of 22.7 W was obtained at 2100 nm, whereas 8.9 W was output at 2200 nm. A core launch efficiency between 80 % and 90 % was estimated from measurements of small signal absorption, however light not coupled into the core is still guided by the all-glass cladding and is partially absorbed. Despite the fiber having an all-glass cladding, core pumping was chosen in this work since it improved long wavelength performance by reducing the fiber length and propagation losses. For operation towards the edge of the tuning range, parasitic lasing at shorter wavelengths (2050 nm–2080 nm) indicative of non-saturable gain appeared when the absorbed pump powers exceeded  $\sim 40$  W, and prevented further power scaling at 2200 nm.

Unidirectional operation of the ring laser was achieved by retro-reflecting the reverse output arm from the outcoupling mirror M1. The reflected signal from M2 in Figure 1 serves as an injected signal for the counterclockwise (CCW) oscillating light,



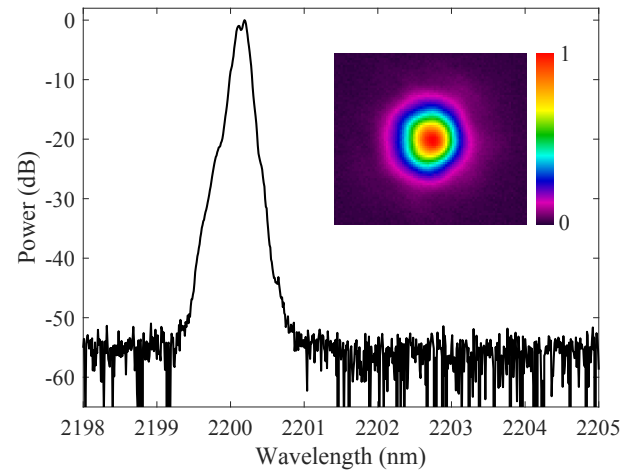
**Fig. 3.** Normalised optical spectra measured with a 2 nm resolution.

such that the presence of any clockwise (CW) light causes growth of the CCW oscillation [p. 535, 12]. Figure 2 shows the degree of unidirectionality measured over the tuning range. Although full extinction of CW light was not achieved using this technique, laser operation with  $>96\%$  of the light circulating CCW was seen over the whole tuning range. The unidirectionality was observed to decrease with wavelength from 99.4 % at 2025 nm to 96.7 % at 2200 nm for unknown reasons that were not further investigated. Notably, unidirectional operation was achieved without the use of a Faraday isolator, which was desirable both due to the limited availability of high power isolators in this spectral regime, and because inclusion of an isolator would add a considerable intra-cavity loss, which is particularly undesirable in this high feedback cavity.

Normalized optical spectra from operating the laser at wavelengths between 2025 nm and 2200 nm in steps of 25 nm are shown in Figure 3. Tuning was limited on the short wavelength side by increasing transmission in the dichroic mirror used for pump coupling, and at long wavelengths by parasitic lasing. Excellent spectral quality is observed across the tuning range, although some short-wavelength ASE is observed when lasing at 2200 nm. The optical signal-to-noise ratio at this wavelength was 45 dB (2 nm spectral resolution), and the in-band power content was measured to  $>99.8\%$ .

A detailed optical spectrum for operation at 2200 nm is shown in Figure 4. Although this particular spectrum is narrow with a full-width half-maximum linewidth of 0.17 nm, the linewidth was observed to vary slightly with pump power, but did not exceed  $\sim 0.5$  nm. Figure 4 also shows the beam profile of the collimated beam at the output from mirror M1, where some beam deformation is observed despite the gain fiber being robustly single mode at this wavelength. This is attributed to the presence of small amounts of cladding light, which was confirmed by imaging the fiber end face. The high feedback cavity design made the beam profile sensitive to the intra-cavity core-to-core coupling, since light not launched into the core was guided by the all-glass cladding. Using a scanning slit beam profiler, the  $M^2$  beam quality was measured to vary between 1.2 and 1.4.

Figure 5 shows the power curve recorded when operating the laser at 2200 nm. The transmission grating used in the tuning cavity had a diffraction efficiency into first order of  $\sim 95\%$  for s-



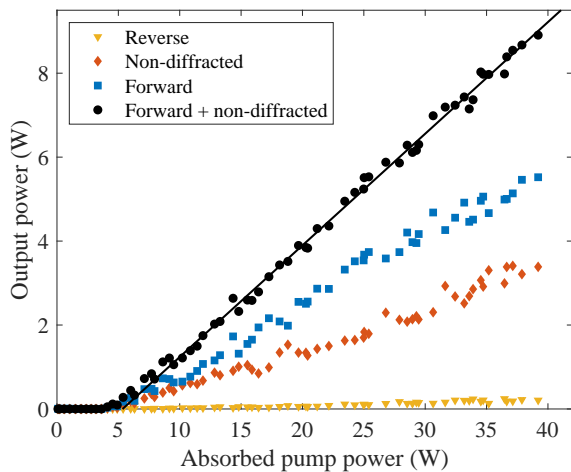
**Fig. 4.** Optical spectrum at 2200 nm measured with a 0.05 nm resolution. The inset shows the beam profile.

polarization, but only  $\sim 30\%$  for  $p$ -polarization. When combined with depolarization that occurred due to the random birefringence of the fiber, this led to a considerable amount of power lost from the cavity through the zeroth order of the diffraction grating. This fraction was found to vary with power and depend on the fiber coiling. For the power curve in Figure 5, 5.5 W was measured from the outcoupling mirror out of a total power of 8.9 W, and the remaining 3.4 W leaked through the grating.

Active polarization control was not implemented in this work. By twisting and coiling the fiber, the power reflected from the output coupler and the power leaking through the grating were observed to be anti-correlated, and the power fraction exiting the output coupler could manually be improved to nearly 90%. However, this was only the case for a specific operating point, and it was not possible to optimize fiber birefringence through twisting and coiling to achieve a predominantly linear polarization at all pump powers. Therefore, the fiber was left loosely coiled and the total power obtained from adding the two output arms is used to evaluate intrinsic laser performance. Alternative methods to solve the polarization issues and get single-aperture output could be using a polarization maintaining fiber or a polarization insensitive diffraction grating.

The slope efficiency at 2200 nm for the total laser output in Figure 5 was 27%. This was measured with respect to absorbed pump power because thermal lensing in the coupling optics caused a power dependent core launch efficiency and hence a non-linear power curve with respect to launched power. Alignment was optimized at maximum power, where a pump absorption of 93% was obtained. The pump absorption was higher for operation at shorter wavelengths where pump saturation was less significant. Figure 6 shows the slope efficiency and threshold from power curves at the different wavelengths. A slope above 55% was obtained at the optimum part of the tuning range between 2050 nm and 2125 nm. This is lower by 10% to 20% compared to experiments with the same fiber in linear cavities with high output coupling [11]. This is attributed to intra-cavity coupling losses combined with the increased impact of core propagation loss in a high feedback resonator.

It was confirmed that higher outcoupling ratios could be used for increasing efficiency in the parts of the tuning range closer to the peak gain, but the high wavelength-selective feedback was

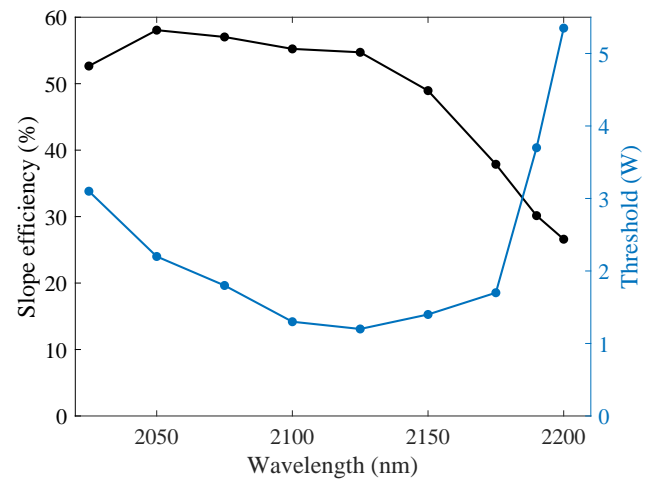


**Fig. 5.** Power curve measured at 2200 nm, showing the combined and separate contributions of forward power from the output coupler (PM1 in Figure 1) and non-diffracted light leaking through the grating (PM2). The laser power circulating in the reverse direction as measured with PM3 is also shown.

found necessary for stable 2200 nm operation. A selection of different output coupling mirrors were tested in the laser, and the mirror that provided the highest possible outcoupling whilst maintaining good spectral quality out to 2200 nm was chosen. The effective feedback to the laser in the current configuration is estimated to 50 % by considering the output coupling from the mirror M1 (20 %), the fraction of non-diffracted light (13 %, estimated from Figure 5), and assuming a realistic core-to-core coupling efficiency of 80 %.

The slope efficiency was nearly constant at  $\sim 55\%$  up to a wavelength of 2125 nm, beyond which it drops monotonically towards 27 % at 2200 nm. Still, even at 2200 nm a reasonable slope efficiency close to 30 % is achieved, which means that power scaling in the 2150 nm–2200 nm spectral region is viable. Further improvements of power and efficiency are expected from optimizing the resonator design, for instance a fixed wavelength all-fiber laser with fiber Bragg gratings.

In conclusion, we have presented a tunable holmium-doped fiber laser targeting long-wavelength operation, and for the first time demonstrated watt-level power from a silica fiber laser operating at 2200 nm. Using a high-feedback ring laser with an in-house developed holmium gain fiber with low  $\text{OH}^-$ -contamination, stable and continuously tunable operation with excellent spectral quality was obtained from 2025 nm to 2200 nm. Unidirectional operation of the ring laser with a contrast better than 25:1 was achieved without the use of a Faraday isolator by retro-reflecting one of the laser output arms. The laser operated with a slope efficiency with respect to absorbed power of 58 % at 2050 nm and 27 % at 2200 nm, and delivered an output power of 5.5 W from a single aperture (8.9 W total) at 2200 nm. Although propagation losses at the infrared absorption edge of fused silica reduces the efficiency towards 2200 nm, these results suggest that power scaling to the multi-tens of watt regime from a single aperture should be possible with the use of improved cavity configurations with reduced intra-cavity losses. To the best of our knowledge, these results represent the highest power from silica fiber lasers operating beyond 2170 nm reported in the published literature, extending the coverage of the 2100 nm–2250 nm



**Fig. 6.** Slope efficiency (black) and threshold (blue) of the laser across the tuning range, both measured with respect to absorbed pump power.

atmospheric transmission window with high power fiber lasers.

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### REFERENCES

1. A. Hemming, N. Simakov, J. Haub, and A. Carter, *Opt. Fiber Technol.* **20**, 621 (2014).
2. A. Sincore, J. D. Bradford, J. Cook, L. Shah, and M. C. Richardson, *IEEE J. Sel. Top. Quant.* **24**, 0901808 (2018).
3. F. Liu, P. Liu, X. Feng, C. Wang, Z. Yan, and Z. Zhang, *Opt. Express* **27**, 8283 (2019).
4. J. Li, Z. Sun, H. Luo, Z. Yan, K. Zhou, Y. Liu, and L. Zhang, *Opt. Express* **22**, 5387 (2014).
5. N. Simakov, A. Hemming, W. A. Clarkson, J. Haub, and A. Carter, *Opt. Express* **21**, 28415 (2013).
6. A. Shirakawa, M. Chen, K. I. Ueda, C. B. Olausson, J. K. Lyngsø, and J. Broeng, *Opt. Fiber Technol.* **16**, 449 (2010).
7. M. P. Kalita, S.-u. Alam, C. Codemard, S. Yoo, A. J. Boyland, M. Ibsen, and J. K. Sahu, *Opt. Express* **18**, 5920 (2010).
8. N. Simakov, Z. Li, Y. Jung, J. M. O. Daniel, P. Barua, P. C. Shardlow, S. Liang, J. K. Sahu, A. Hemming, W. A. Clarkson, S.-u. Alam, and D. J. Richardson, *Opt. Express* **24**, 13946 (2016).
9. O. Humbach, H. Fabian, U. Grzesik, U. Haken, and W. Heitmann, *J. Non-Cryst. Solids* **203**, 19 (1996).
10. S. O. Antipov, V. A. Kamynin, O. I. Medvedkov, A. V. Marakulin, L. A. Minashina, A. S. Kurkov, and A. V. Baranikov, *Quantum Electron.* **43**, 603 (2013).
11. P. C. Shardlow, N. Simakov, A. Billaud, J. M. O. Daniel, P. Barua, J. K. Sahu, A. Hemming, and W. A. Clarkson, *CLEO Eur. pp. CJ-11-4* (2017).
12. A. Siegman, *Lasers* (University Science Books, 1986).
13. M. Hercher, M. Young, and C. B. Smoyer, *J. Appl. Phys.* **36**, 3351 (1965).

## FULL REFERENCES

1. A. Hemming, N. Simakov, J. Haub, and A. Carter, "A review of recent progress in holmium-doped silica fibre sources," *Opt. Fiber Technol.* **20**, 621–630 (2014).
2. A. Sincore, J. D. Bradford, J. Cook, L. Shah, and M. C. Richardson, "High Average Power Thulium-Doped Silica Fiber Lasers: Review of Systems and Concepts," *IEEE J. Sel. Top. Quant.* **24**, 0901808 (2018).
3. F. Liu, P. Liu, X. Feng, C. Wang, Z. Yan, and Z. Zhang, "Tandem-pumped, tunable thulium-doped fiber laser in 2.1  $\mu\text{m}$  wavelength region," *Opt. Express* **27**, 8283–8290 (2019).
4. J. Li, Z. Sun, H. Luo, Z. Yan, K. Zhou, Y. Liu, and L. Zhang, "Wide wavelength selectable all-fiber thulium doped fiber laser between 1925 nm and 2200 nm," *Opt. Express* **22**, 5387–5399 (2014).
5. N. Simakov, A. Hemming, W. A. Clarkson, J. Haub, and A. Carter, "A cladding-pumped, tunable holmium doped fiber laser," *Opt. Express* **21**, 28415–28422 (2013).
6. A. Shirakawa, M. Chen, K. I. Ueda, C. B. Olausson, J. K. Lyngsø, and J. Broeng, "High power ytterbium fiber lasers at extremely long wavelengths by photonic bandgap fiber technology," *Opt. Fiber Technol.* **16**, 449–457 (2010).
7. M. P. Kalita, S.-u. Alam, C. Codemard, S. Yoo, A. J. Boyland, M. Ibsen, and J. K. Sahu, "Multi-watts narrow-linewidth all fiber Yb-doped laser operating at 1179 nm," *Opt. Express* **18**, 5920–5925 (2010).
8. N. Simakov, Z. Li, Y. Jung, J. M. O. Daniel, P. Barua, P. C. Shardlow, S. Liang, J. K. Sahu, A. Hemming, W. A. Clarkson, S.-u. Alam, and D. J. Richardson, "High gain holmium-doped fibre amplifiers," *Opt. Express* **24**, 13946–13956 (2016).
9. O. Humbach, H. Fabian, U. Grzesik, U. Haken, and W. Heitmann, "Analysis of OH absorption bands in synthetic silica," *J. Non-Cryst. Solids* **203**, 19–26 (1996).
10. S. O. Antipov, V. A. Kamynin, O. I. Medvedkov, A. V. Marakulin, L. A. Minashina, A. S. Kurkov, and A. V. Baranikov, "Holmium fibre laser emitting at 2.21  $\mu\text{m}$ ," *Quantum Electron.* **43**, 603–604 (2013).
11. P. C. Shardlow, N. Simakov, A. Billaud, J. M. O. Daniel, P. Barua, J. K. Sahu, A. Hemming, and W. A. Clarkson, "Holmium doped fibre optimised for resonant cladding pumping," *CLEO Eur. pp. CJ–11–4* (2017).
12. A. Siegman, *Lasers* (University Science Books, 1986).
13. M. Hercher, M. Young, and C. B. Smoyer, "Traveling-wave ruby laser with a passive optical isolator," *J. Appl. Phys.* **36**, 3351 (1965).