Power Scaling of Resonantly Pumped Holmium-Doped Fiber Lasers

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Holmium-doped fibers enable power scaling at an eye-safe wavelength and provide many advantages over conventional ytterbium and thulium-doped fiber lasers. The longer wavelength of operation facilitates the avoidance of parasitic non-linear effects that limit the achievable output power of more traditional ytterbium-doped fiber lasers. Whilst the gain in thulium-doped fibers decreases markedly at wavelengths beyond 2.05 µm, holmium-doped fibers operate efficiently at 2.1 µm which is critical for applications requiring efficient propagation through the atmosphere. We present tuning experiments of cladding-pumped holmium fiber lasers over the 2.05-2.15 µm region. We also present a high power, monolithic holmium-doped fiber laser, cladding-pumped by an array of efficient 1.95 µm thulium-doped fiber lasers. This laser produced 407 W at 2.12 µm from a robustly single-mode fiber.

The spectral region around 2.1 µm is of particular interest due to its atmospheric propagation properties which are relevant to remote sensing applications and high power laser propagation. For applications requiring long propagation distances and in conditions with poor atmospheric transmission operation at 2.1 µm is advantageous due to the reduced losses associated with aerosol absorption and Rayleigh scattering. Of particular interest is the operation of high power laser sources in this spectral region which have only recently been demonstrated at the kW power level. Another significant benefit is the eye-safety aspect of the laser source with the maximum permissible exposure (MPE) being >3 orders of magnitude higher in the 2-2.2 µm region than at 1 µm [1].

Operation at ~2 µm also enables suppression of deleterious non-linear effects such as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) which otherwise limit high-power narrow line-width operation of fiber lasers. Consequently 2 µm fiber lasers are better suited to applications such as spectral beam combination (SBC) and coherent beam combination (CBC). More specifically the core diameter of a single-mode fiber scales linearly with wavelength and hence the mode field area increases four-fold between 2 µm and 1 µm. This provides a significant advantage for 2 µm fiber laser systems in terms of reducing the stimulated Brillouin scattering (SBS) threshold. Also, the SBS gain line-width is reduced in comparison with 1 µm which increases the efficiency of SBS suppression by techniques such as the application of temperature gradients, strain gradients and phase modulation to the source [2]. For 2.1 µm operation in silica, the first stimulated Raman stokes field occurs at >2.25 µm where the background loss of silica is exponentially increasing. As a result, SRS is of little concern to holmium-doped silica fiber lasers. Overall 2 µm fiber lasers present a compelling case for use in high power narrow line-width applications.

To date the power scaling of fiber lasers in the 2 µm spectral region has been dominated by thulium-doped fiber lasers. More than 1 kW of output power has been achieved by a 0.79 µm diode laser pumped all-fiber two stage amplifier [3], and 415 W from a monolithic fiber laser cavity resonantly pumped at 1.57 µm using Er:Yb fiber lasers [4]. Most notably for beam combination applications was the demonstration of a 608 W narrow line-width (<5 MHz) amplifier [5]. We have previously demonstrated single-mode, monolithic, thulium fiber lasers operating at >150 W output power and 60% slope efficiency with respect to launched 0.79 µm pump power; equating to wall-plug efficiencies of 20-24% [6]. Further power scaling of thulium fiber lasers is currently limited by pump diode brightness, and the thermal performance of polymer coatings. Holmium-doped fiber lasers on the other hand are able to leverage the development of these efficient, high power thulium-doped fiber lasers as pump sources at 1.95 µm.

Resonantly pumped holmium-doped fiber lasers present an opportunity to further power scale 2 µm fiber lasers and amplifiers while avoiding the current limitations on the power scaling of thulium fiber lasers. The resonantly cladding pumped architecture allows the holmium-doped fiber laser to be pumped by a number of high brightness, mature thulium fiber lasers operating well below their failure point. In contrast to power scaling a single thulium fiber laser device close to its operating limit, this enables the majority of the heat load to be distributed across an array of pump lasers, reducing thermal constraints on the system. The low quantum defect offered by a 1.95 µm pumped, holmium-doped fiber laser system operating at 2.1 µm then offers a route to an efficient final high power amplifier. The use of high brightness thulium pump lasers relaxes the brightness requirements on the cladding pumped holmium-doped fiber. As a result a reduced NA can be used allowing an all-glass fluorine-doped cladding to be utilized, thereby removing the need for the use of a fluoro-polymer cladding while still maintaining power scalability. Finally, thulium-doped fibers used for 0.79 µm diode pumped lasers use a high thulium dopant concentration to achieve efficient cross-relaxation. This requires a pedestal structure to produce good beam quality output, complicating fabrication and limiting the NA achievable. In contrast holmium-doped fiber lasers require a simple low dopant concentration core composition which enables flexibility in core design and fabrication.

Tuning Results

Experimental tuning curves obtained for core and cladding pumped holmium fiber lasers are depicted in Figure 1. The results were obtained using a Littrow configuration, with the dispersive element forming the high reflectivity end of the laser cavity and with pumping achieved using a dichroic mirror to combine pump and laser radiation. The output coupler was provided by the Fresnel reflection from the cleaved fiber end. The maximum output powers demonstrated were 3.2 W for the core pumped laser, and 14.4 W and 19.4 W for the 3.5 m and 6.5 m long cladding pumped lasers respectively.

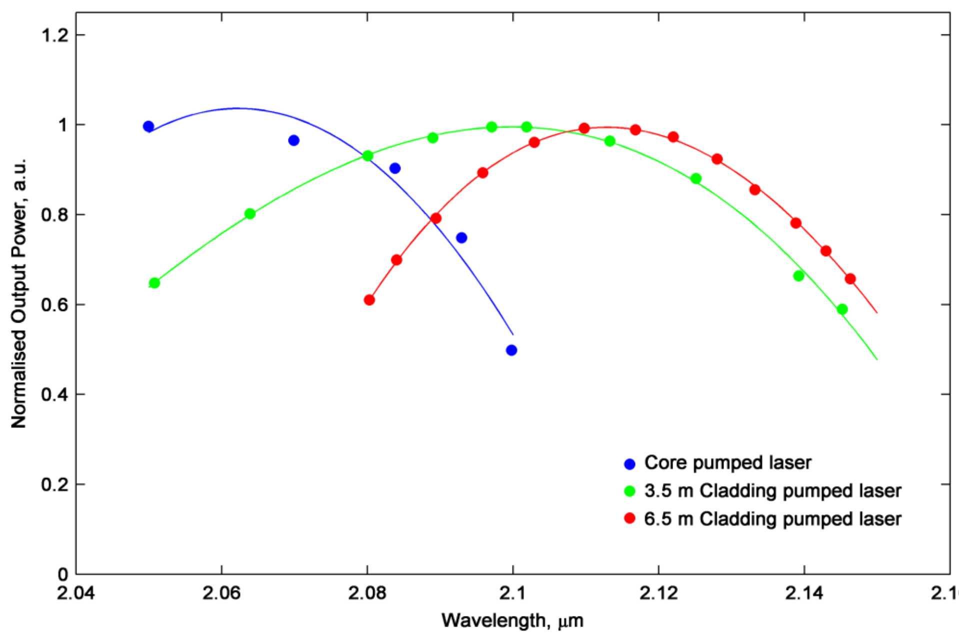

Figure 1. Tuning curves of core pumped, and 3.5 m and 6.5 m long cladding-pumped holmium-doped fiber lasers.

For low power applications where system efficiency is less significant, a reduced length cladding pumped holmium-doped fiber provides access to the entire 2.05-2.15 µm region for both pulsed and cw operation. This wavelength range is useful for CO_2 DIAL, Doppler LIDAR and free-space optical communications. This is not possible with thulium fiber lasers which are limited to operation within 1.85-2.05 µm due to the diminishing thulium emission cross-section.

For systems where efficient conversion is required, a longer length of fiber is necessary to increase pump absorption. These lasers typically operate efficiently in the 2.10-2.13 µm region providing access to a 30 nm bandwidth. Given the reduced nonlinear effects experienced in single-mode holmium-doped fibers, it is feasible to spectrally combine many narrowband sources across this relatively wide (30 nm) operating window. In comparison the transmission window for an efficient thulium fiber laser is at 2.03 µm and spans <5 nm.

Operation beyond 2.15 µm is limited by fundamental background IR silica absorption as well as absorption losses due to OH^- contamination. In particular the cladding pumped holmium fiber used here has a relatively high OH^- concentration of 14±2 ppm. Future iterations of this fiber will have lower OH^- concentration which should allow further extension of this tuning range.

High Power Laser Operation

We have previously demonstrated the first efficient operation of a resonantly cladding-pumped holmium fiber laser with up to 140 W of output power [7]. This initial result was a free-space demonstration. One of the advantages of the resonantly pumped holmium fiber laser architecture is its potential to be implemented in a monolithic configuration. Our recent results have demonstrated such a monolithic implementation of this laser architecture.

The holmium laser is pumped by an array of monolithic thulium fiber lasers typically operating at ~160 W each at 1.95 µm. These are combined using a fused pump combiner which results in ~1 kW of output pump power at 1.95 µm from a 112 µm, 0.24 NA passive Fluosil-clad fiber. This pump combiner output is then spliced to a holmium fiber laser, consisting of 6.5 m of Fluosil clad holmium fire and a high reflector (HR) fiber Bragg grating (FBG). The Fresnel reflection from the cleaved output facet serves as the output coupler.

The output power is plotted in Figure 2. A maximum output power of 407 W was achieved. The laser exhibits a roll-over of forward propagating power as a function of pump power along with an increase in reverse propagating power. The increase in reverse propagating power as well as a shift in the operating wavelength and spectral broadening of the output indicates that the reflectivity and bandwidth of the HR FBG is changing as a function of power, potentially due to heating associated with absorption in the fiber core at the lasing wavelength of 2.12 µm. A typical near-field profile is also shown from this robustly single-mode fiber.

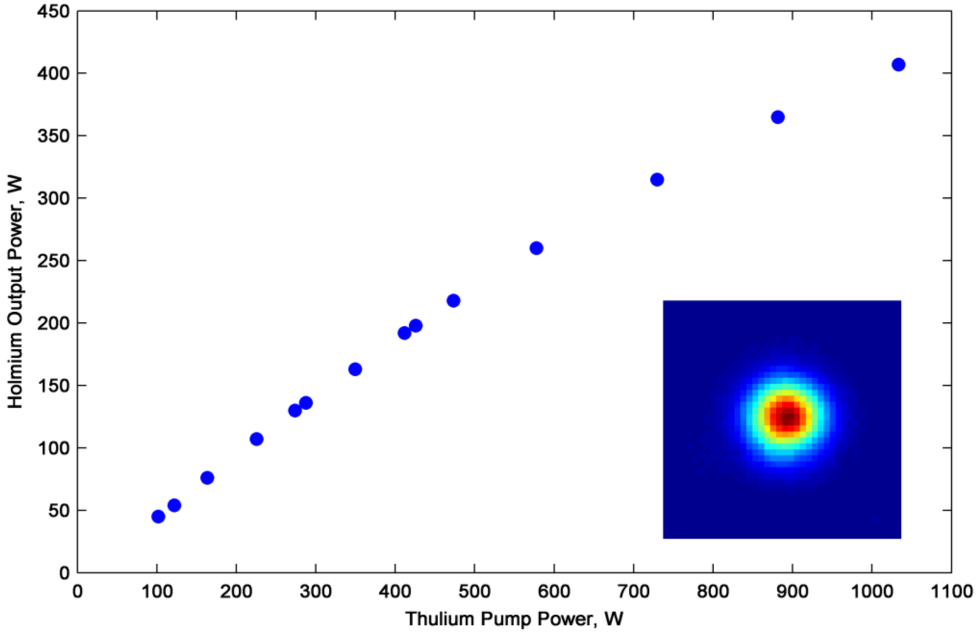

Figure 2. Output power and typical beam profile of the single-mode holmium-doped fiber laser.

Conclusions and Future Work

In the 2 µm spectral region resonantly pumped holmium fiber lasers show great promise for power scaling into the kW regime and beyond. We have demonstrated an output power of 407 W limited only by pump power and grating performance. The laser was demonstrated in a monolithic configuration and demonstrates the potential power scalability of this laser architecture.

As well as high power operation we investigated the tuning characteristics of both core and cladding pumped holmium-doped fiber lasers. The cladding pumped results indicate that high power resonantly pumped holmium-doped fiber lasers are able to access atmospheric transmission windows around 2.1-2.15 µm. The combination of this broad tunability and power scaling potential indicate that this laser architecture will address high power laser applications utilizing spectral and coherent beam combination.

Future work will investigate increasing the efficiency of this laser system by optimizing the core composition as well as implementing narrow line-width amplifier systems.

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