High Power Holmium Fiber Lasers

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Abstract *Sources based on resonantly cladding pumped holmium-doped fibres have been demonstrated at >400 W CW or with pulse energies of >2 mJ. We review the enabling technologies, and discuss the challenges associated with high power operation of fibre lasers at 2.1 µm.*

Introduction

Sources at 2.1 µm are required for a variety of applications such as remote sensing, free-space optical communication, and as pump sources for mid-infrared optical parametric oscillators. Sources in this wavelength region have a much higher retinal maximum permissible exposure which may be preferable in many applications[1]. Operating at 2.1 µm also offers significant advantages in atmospheric transmission by allowing the strong H_2O and CO_2 resonances that occur at around 2 µm to be avoided. This wavelength is also less susceptible to atmospheric Rayleigh scattering in comparison to 1 µm sources, thereby providing less sensitivity to environmental conditions.

Traditionally these requirements have been addressed by holmium-doped crystalline materials such as YAG and YLF. However the power scaling of these sources is limited by beam distortion due to thermally induced stresses. Fibre lasers present an attractive robust, monolithic alternative that is amenable to power scaling while preserving excellent beam quality.

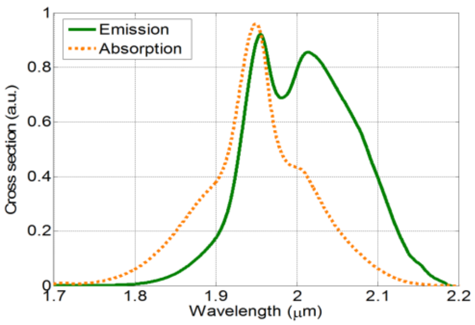
Holmium-doped fibres are an emerging technology that enables high power and efficient operation of silica fibre lasers across the 2.04 – 2.17 µm range. Previously these sources have relied on core-pumped approaches, using either 1.15 µm ytterbium, or 1.95 µm thulium fibre laser pump sources. As a result the output powers achieved have been limited to <10 W[2-4].

In this paper we provide an overview of the enabling technologies and challenges to achieving high power operation of resonantly cladding pumped holmium-doped fibre lasers.

Cladding pumped holmium fibre design

When incorporated into amorphous hosts, such as silica, holmium exhibits a much broader emission at 2.1 µm than it does in a crystalline host. This is an essential requirement in optical communications applications where the accessible bandwidth directly impacts the number of possible channels and also in ultrafast pulse generation applications. Typical absorption and emission spectra are shown in Fig. 1a. The peak of the absorption occurs at 1.95 µm and the low quantum defect (~8%) associated with this transition is extremely attractive for power scaling.

The 1.95 µm pump wavelength is not compatible with conventional low index acrylate coated double clad fibre designs, which are typically strongly attenuated at this wavelength. In order to operate efficiently, the cladding of a resonantly pumped holmium-doped fibre must provide low loss guidance for the pump radiation[5,6]. This can be achieved by an internal fluorine doped layer (Fluosil®). The end view of a typical holmium-doped fibre is shown in Fig. 1b. The typical numerical aperture (NA) achievable is ~0.24 with respect to un-doped silica. Using this approach we have demonstrated robustly single-mode, large-mode-area and polarization maintaining fibres that are able to be efficiently pumped at 1.95 µm[6,7].



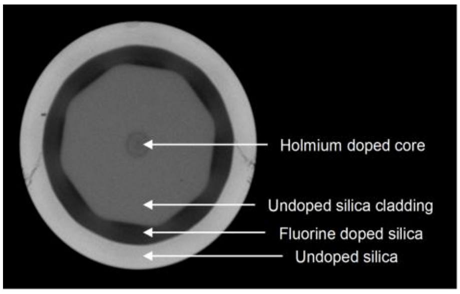


Fig. 1: a) Holmium absorption and emission cross sections **b)** End view of a holmium-doped fibre

1.95 µm pump laser sources

An enabling technology for any high power laser is a suitable pump source. As we have discussed, pumping at 1.95 µm necessitates a low NA cladding and consequently high brightness pump sources are required. The required brightness is much higher than is currently achievable with diode lasers at this wavelength.

Diode pumped thulium fibre laser technology is maturing rapidly with a growing interest among industry and fibre component manufacturers. In particular 0.79 µm diode pumped thulium-doped fibre lasers have been shown to operate efficiently (>60%) across the 1.9 – 2.05 µm wavelength range. A number of high power results have been demonstrated, >600 W from a single stage thulium amplifier[8] and >1 kW from a dual stage amplifier at 2.04 µm[9]. We have previously demonstrated robustly-single mode, monolithic, all-fibre thulium lasers operating at 1.95 µm with power levels exceeding 180 W[10]. The active fibre used in these lasers had a cladding diameter of 250 µm and required relatively high brightness diode pump sources. We have also demonstrated similar performance from a thulium-doped fibre laser (TDFL) with a 400 µm diameter cladding. This relaxes the requirement on 0.79 µm pump brightness even further and is able to be pumped using a diode coupled into an 800 µm diameter, 0.22 NA fibre.

As the diode pumped thulium-doped fibre laser technology becomes more widely adopted in industry, we anticipate that both the cost of 0.79 µm fibre coupled diodes will decrease and the power and brightness levels will increase. Many companies are now demonstrating new products with increasing power and brightness levels in this wavelength range.

The typical slope efficiency from a TDFL is shown in Fig. 2. The output slope efficiency is 60% with respect to launched 0.79 µm pump power. Given that diodes in this wavelength range operate with a slope efficiency of ~40%, this provides an excellent wall-plug efficiency of ~24%.

Due to the high brightness of the output of these thulium lasers, it is possible to launch many of them into the cladding of a single holmium-doped fibre. We have demonstrated 7→1 and 11→1 fused pump combiners, with > 1 kW of 1.95 µm radiation launched into a 112 µm, 0.22 NA fibre with virtually no heating.

As well as providing brightness levels suitable for pumping holmium-doped fibres, these thulium pump sources alone are of great interest for a range of materials processing applications.

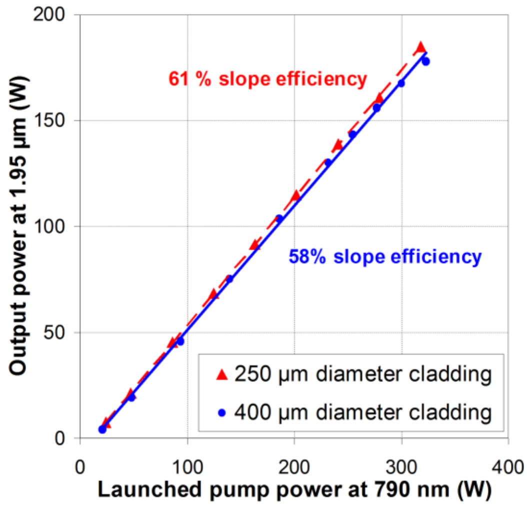


Fig. 2: Output power vs. launched pump power for thulium-doped fibre lasers operating at 1.95 µm

Holmium-doped fibre laser operation

The efficient operating range of a resonantly cladding pumped holmium-doped fibre extends from 2.04 – 2.17 µm[11]. This provides excellent access to an atmospheric transmission window at wavelengths > 2.1 µm as shown in Fig. 3. In comparison, thulium-doped fibre lasers are typically limited to operation at < 2.05 µm. In applications such as remote sensing and free-space optical communications, the ability to access the atmospheric transmission windows at higher powers and with improved eye safety is essential.

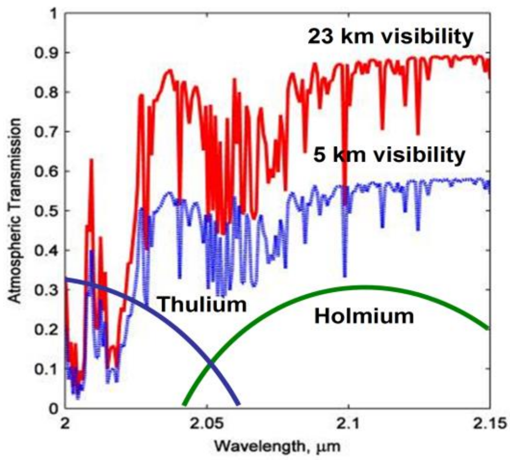


Fig. 3: MODTRAN™ Atmospheric transmission for 5 km path length for 5 km and 23 km visibility conditions. Overlaid are the tuning ranges of cladding-pumped holmium and thulium-doped fibre lasers.

CW fibre lasers and amplifiers with output power levels of 407 W and 265 W have been demonstrated in monolithic, all-fibre systems at 2.11 – 2.13 µm[12,13]. The output power vs. launched power of one such system is shown in Fig 4[13]. We have also investigated pulsed fibre laser operation and demonstrated a linearly polarised amplifier operating at >10 dB gain and producing pulses with 2.25 mJ of output energy and pulse duration of 20 ns[7].

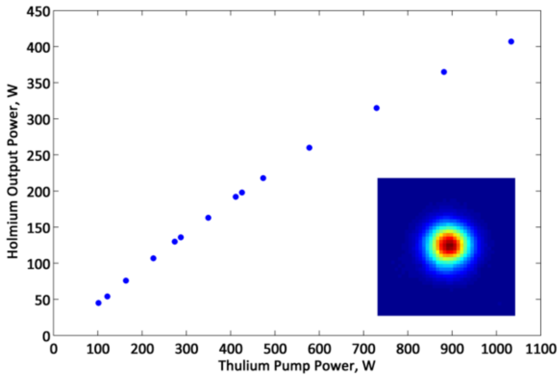


Fig. 4: Output power vs launched power of a holmium-doped fibre laser operating at 2.12 µm[13]

Discussion

We have discussed the requirements on the design of active holmium-doped fibres to enable efficient resonant pumping. An inner Fluosil layer provides low loss confinement of the pump radiation.

We have also reviewed suitable pump sources for holmium-doped silica fibres. Thulium-doped fibre lasers provide an efficient and power scalable method of meeting the brightness requirements for this architecture.

The efficient operating range of cladding pumped holmium-doped fibres has been demonstrated to extend over 130 nm from 2.04 - 2.17 µm[11]. This operating range overlaps with an atmospheric transmission window beyond 2.1 µm, and is less sensitive to atmospheric effects in comparison to shorter wavelengths. We expect these sources will be relevant for free-space optical communication systems where excellent atmospheric transmission and eye-safety are essential considerations.

Conclusion

We have reviewed some of the enabling technology and recent results from a variety of resonantly cladding-pumped holmium-doped fibre sources. Due to the eye-safety advantages, excellent atmospheric transmission and broad band operation, we anticipate that these fibres will find utility in a variety of applications at a range of power levels.

We will present recent high power CW and pulsed results that have been obtained from holmium-doped silica fibres.

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