Watt-level Holmium-doped Fibre Amplifiers Pumped by Broadband Thulium-doped ASE Sources at 1860 nm

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Abstract *We report the design and demonstration of novel 2050 nm Watt-level Ho-doped fibre amplifiers that are pumped with broad spectrum Watt-level Tm-doped ASE sources centred at 1860 nm instead of conventional narrow linewidth semiconductor or fibre laser sources. Our approach is simpler and more cost effective than the standard laser based pumping means, and leads to similar amplifier performance.*

Introduction

Two-micron holmium-doped fibre (HDF) amplifiers and lasers [1,2] have an important role to play in many space and physics applications which include: 1) Free-space transmission between earth and space in low atmospheric attenuation wavelength bands (e.g., 2039 nm and 2130 nm), 2) Generation of high energy 3-5 µm signals using 2.1 µm OPO lasers, 3) Remote molecule sensing and eye-safe LIDAR imaging, 4) Physics experiments based on atom cooling, trapping, and manipulation for quantum computing applications, and 5) Future gravity wave interferometers operating at 2051 nm.

HDFs with their broad emission spectrum (from 2 to 2.15 µm) and high optical conversion efficiency (>80%) are quite attractive for 2 µm sources and amplifiers for these current and future physics and engineering applications. For the HDF amplifiers (HDFAs) and lasers to have a major adoption into these many applications, they need to come in disruptive designs combining several features that include 1) a good electrical-to-optical conversion efficiency, 2) a high power-stability, 3) established reliability in small form-factor packages, and 4) cost-effective architectures.

In this paper we report the design and demonstration of novel 2 µm broadband Watt-level HDFAs that are pumped with broad spectrum Watt-level Tm-doped amplified spontaneous emission (ASE) sources instead of conventional semiconductor or fibre laser sources. Our approach is simpler and more cost effective than the standard laser-based pumping means and leads to similar amplifier performance.

Our innovative approach is based on the broadband ASE-optical pumping of the active fibre of the amplifier instead of conventional amplifier configurations that rely on pumping from semiconductor or fibre laser pumps. Our ASE pumped HFDA alternative offers the following advantages: 1) Simple and versatile pumping design, 2) Reduced cost, 3) Equivalent or superior optical performance, 4) Higher reliability and better wall plug efficiency, and 5) Compatibility with SWAP for both terrestrial and space-based applications.

Architecture of the ASE Pumped HDFA and Simulation Results

In this section we present an initial simulation study illustrating the performance of a one-stage HDFA pumped by an ASE source. Figure 1 shows the optical configuration of the HDFA under study. The input signal, P_{in}, at a wavelength of 2050 nm with a 0 dBm (1 mW) CW power, is coupled into the active Ho-doped fibre F1 through isolator I1 and wavelength division multiplexer WDM1. A broadband ASE pump light source is coupled into F1 through WDM1 and pumps the Holmium ions in the fibre to produce gain within the emission band (i.e., from 2 to 2.15 µm). The ASE pump has a Gaussian spectral shape centred at λ_0 = 1860 nm [3] with a 3-dB width of $\Delta\lambda$ and a CW ASE output power of P_{pump}. As a result, the signal is amplified along the 2.5-m-long single-clad Ho-doped fibre F1 and exits after isolator I2.

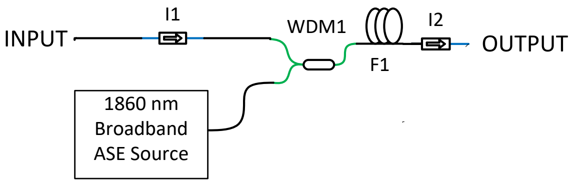

Fig. 1. Configuration of a single stage HDFA co-pumped with a broadband ASE source.

Figure 2 plots the spectral evolution of a representative experimental two-stage Tm-doped ASE source as a function of output power P_{out} [5]. This graph demonstrates that for a P_{out} up to 1.25 W the ASE source exhibits similar behaviour in terms of centre wavelength (e.g., 1860 nm) and 3 dB or FWHM emission bandwidth (50 nm), while exhibiting no instability or self-lasing. It should be noted that the 1860 nm centre wavelength coincides with one of the pump wavelengths that produces the best power conversion efficiency in the Ho-doped fibre amplifier [3,6].

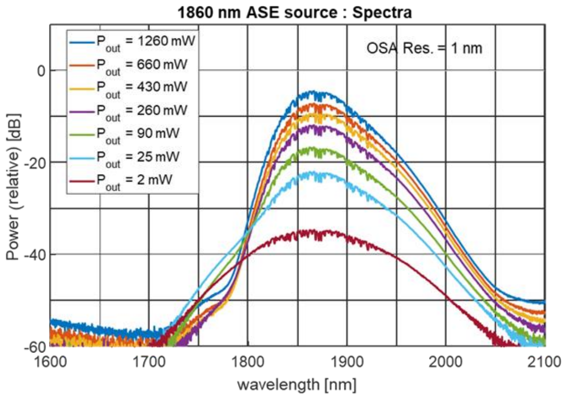

Fig. 2. Experimental output spectra for a representative two-stage Tm-doped ASE source vs. CW ASE output power.

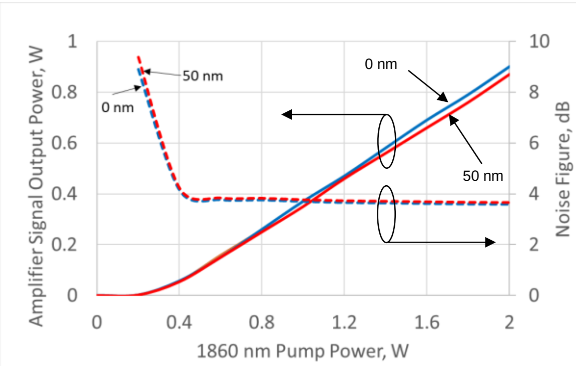

Fig. 3. HDFA P_{out} and NF vs. ASE pump power and Δλ.

In using the 1860 nm ASE source as a pump for our single stage HDFA in Figure 1, we have simulated the P_{out} and noise figure performance for 1 mW input signal power P_{in} at 2050 nm wavelength [4]. The 3 dB width of the ASE pump was set to 50 nm to match the experimental 3 dB spectral width, and a monochromatic pump source with a negligible linewidth (i.e., 0 nm) was also plotted for comparison. The simulation results in Figure 3 for the 50 nm (3 dB) ASE source indicate that 1) the P_{out} increases linearly with pump power, with a P_{out} of 0.9 W for a 2 W pump and a 38% slope efficiency, and 2) the NF value plateaus around 3.7 dB for more than 0.5 W of 1860 nm power. In contrast, with the monochromatic source, there is no change in the NF evolution and an improvement of P_{out} conversion efficiency to 40%. In other terms, the ASE pump produces similar performance to the monochromatic laser pump.

In the two stage ASE source configuration, the 3 dB width of the spectral emission can be selected by inserting a mid-stage bandpass filter centred at a wavelength within the natural ASE emission spectrum. Basically, the first stage seeds and also saturates the second stage Tm-doped fibre amplifier to extract maximum ASE output power. As an example, we have simulated [4] the performance of a two-stage ASE source with a bandpass filter centred at 1860 nm with variable spectral widths from 0.5 nm to 50 nm.

The corresponding evolution of the ASE output power as a function of wavelength and spectral width is plotted in Figure 4. As the filter width decreases, the peak power increases while the total power remains the same. This design enables us to concentrate the ASE power over a limited bandwidth and thus optimize the pumping efficiency of the HDFA. In this plot we note that the total or CW power of the ASE source is constant at 2.0 W for all the spectral widths investigated, from 0.5 nm to 50 nm.

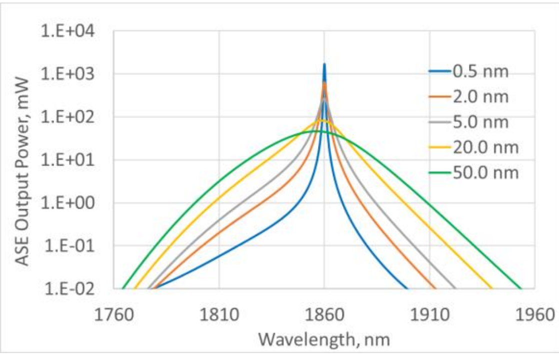

Fig. 4. Simulated output spectra for a 2 W average output power TDF ASE source, as a function of 3 dB BPF bandwidth. Resolution bandwidth is 1 nm, centre wavelength of filter = 1860 nm.

To establish the effect of spectral bandwidth on the output power of the HDFA, we conducted simulations [4] on the Ho-doped fibre amplifier in Figure 1 by setting the pump power to 1.4 W and changing the spectral width from 0.5 nm to 80 nm. Figure 5 plots the simulated results of P_{out} as a function of the spectral width for P_{pump} = 1.4 W. For reference purposes the output power using a monochromatic pump source is plotted with a red star on the left-hand axis. The broadband ASE source is just as efficient as the monochromatic laser source for spectral widths Δλ below 20 nm. These results confirm the effectiveness of using broadband ASE pump sources for Ho-doped fibre amplifiers.

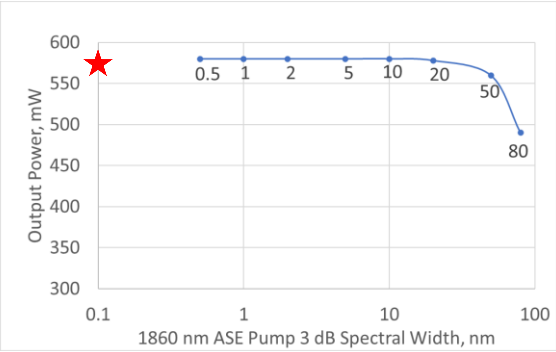

Fig. 5. Simulated signal output power at 2050 nm as a function of pump spectral width Δλ (blue data points).

Figure 6 shows the simulated output spectrum for the HDFA under study (Figure 1), for a pump 3 dB spectral width of 10 nm and a total ASE pump power of 1.4 W. The broad spectral nature of the ASE pump source is clearly displayed in the 1860 nm region of the spectrum. The amplified output signal portion of the spectrum from 1950 nm to 2200 nm is identical to the spectrum obtained with a monochromatic pump source. The optical signal to noise ratio (OSNR) is 65 dB in a resolution of 0.1 nm.

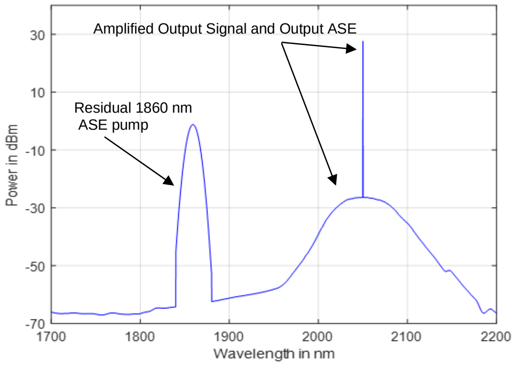

Fig. 6. Simulated output spectrum of the co-pumped HDFA for ASE Δλ = 10 nm, P_{in} = 0 dBm at 2050 nm, and RBW = 1.0 nm.

Experimental Results

Initial experimental results for the amplifier in Figure 1 are plotted in Figure 7, which shows signal output power vs. pump power for the single stage HDFA using both a broadband ASE source centred at 1860 nm (FWHM = 60 nm) and a narrowband fibre laser source at 1860 nm. We observe that the output power performance of the HDFA is similar when pumped with both a broadband ASE source and a narrow band fibre laser source, with a difference of -0.5 dB between the ASE pumped amplifier and the fibre laser pumped amplifier. This difference in output power is entirely consistent with the simulations in Figure 5, and confirms the predictions that ASE pumping is equally as effective as single frequency fibre laser pumping. The experimental noise figure for 0 dBm input power is 4.2 ± 1 dB which is consistent with simulations in Figure 3.

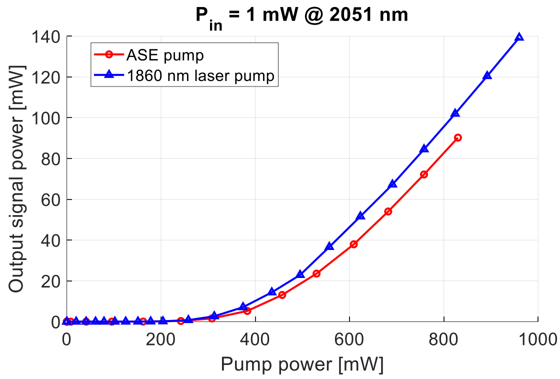

Fig 7. Experimental P_{out} vs. P_{pump} for ASE pumping and fibre laser pumping.

Figure 8 plots the output spectra for the HDFA with both broadband 1860 nm ASE pumping (blue) and single frequency 1860 nm fibre laser pumping (red). We see that the output powers and HDFA ASE output within the signal band of 2000–2100 nm are essentially identical as expected, while the pump band feedthrough in the 1800–2000 nm band is consistent with expectations. Further experimental data and simulations will be presented at the conference.

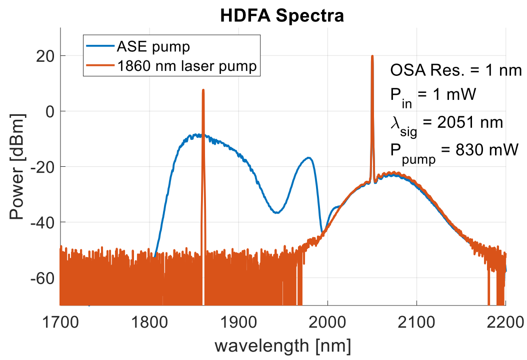

Figure 8. Experimental output spectra for 1860 nm broadband ASE pumping and 1860 nm single frequency fibre laser pumping.

Summary and Conclusions

We have reported and demonstrated the design and operation of an ASE pumped Ho-doped fibre amplifier operating in the 2000 nm band. Our ASE pumped HDFA exhibits similar performance to an HDFA pumped with a narrow linewidth semiconductor or fibre laser source. Overall, the use of a broadband ASE pump source to pump HDFAs offers great pump versatility in a cost-effective configuration that does not compromise amplifier performance. Its use can be generalized to other rare-earth doped amplifiers and expanded to multi-stage amplifiers and fibre lasers with higher output powers.

References

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