# LD-seeded thulium-doped fibre amplifier for $CO_2$ measurements at 2 μm

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Carbon dioxide ($CO_2$) measurements are of interest to the aviation industry because of the need to reduce net $CO_2$ emission from aero ("jet") engines [1] as well as for engine diagnostics. Chemical Species Tomography (CST) is a technique that uses an optical source for multi-path integrated absorption measurements and from those calculates a 2-dimensional image of target gas concentration [2]. In FLITES [3], we target CST of $CO_2$ in aero-engine exhaust plumes with diameter up to ~ 1.4 m at wavelengths around 2 μm. Typically, single-path absorption measurements are carried out using distributed feedback (DFB) diode lasers with powers of ~2 mW. For CST, however, it would be necessary to use over one hundred separate paths, and thus laser sources, to achieve adequate spatial and temporal resolution. It is essential that a single CST-capable laser source, with total power above 1 W, is developed and the light distributed into the individual paths using optical fibre components.

Here, we use a single-stage thulium doped fibre amplifier (TDFA) [4] to amplify the output power from a modulated 2 μm DFB diode laser that has suitable characteristics for CST of $CO_2$. Figure 1 shows our setup. A 793 nm pump diode with a 100 μm, 0.22 NA core pigtail (DILAS) is spliced to the forward-direction pump port of a 4.5 m long Tm-doped GT-Wave fibre [5]. The fibre, which was fabricated in house, has a 0.21 NA, ~8 μm diameter aluminosilicate core doped with 950±100 ppm $Tm^{3+}$ by weight. The pump absorption exceeds 99% at the highest pump power. The seed laser (Eblana Photonics) can provide 2 mW of cw output power at ~1997 nm with an instantaneous linewidth < 1 MHz. Of this, 0.8 mW is launched into the Tm-doped fibre. For CST, the seed laser is driven by a 10 ms long current ramp which scans the wavelength across the absorption line. As a side-effect, the launched instantaneous power varies between 0.26 mW and 1.58 mW. Even with this low seed power, the amplifier is largely saturated with gain > 35 dB at maximum average output power of 2.5 W.

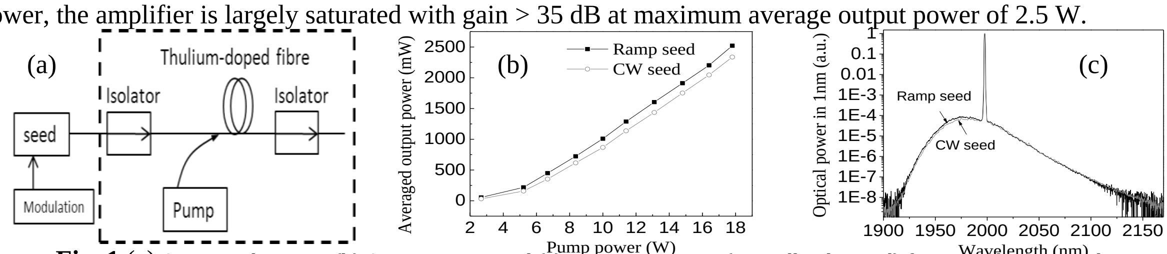


**Fig. 1** (a) System schematic. (b) Output power and (c) output spectrum (virtually identical) for cw and ramp seed.

In addition to the ramp, a 500-kHz sinusoidal modulation is applied to the seed laser drive current, in order to reduce the effects of noise inherent in an aero-engine test rig. This technique is known as wavelength modulation spectroscopy (WMS) and has been used in a number of industrial environments [6]. While the drive current modulation serves to sweep and modulate the wavelength, it also affects the seed power. The TDFA does not modify the wavelength modulation, but for the power it acts as a high-pass filter with a power-dependent cut-off frequency [7]. The TDF's saturation energy is ~ 22 μJ at 1997 nm, from which we can estimate a time constant of ~7 μs at a signal power of 3.2 W out from the Tm-doped fibre (this drops to 2.5 W after the output isolator). Thus, while the fast power modulation will be largely unaffected, the slow ramping will be suppressed. Our measurements confirm this suppression, which is beneficial in that it helps to reduce the overall power requirements. While there is a potentially detrimental modulation of amplified spontaneous emission (ASE) that results as the TDFA gain adjusts to compensate for the ramping of the seed power, an optical filter or a higher-power seed would reduce the ASE power as well as any degradation thereof. Our ASE power is 0.01% of the signal power when measured in 1 nm and 0.5% in total. Furthermore, by going to higher signal output powers, smaller cores with smaller saturation energy, or lower frequencies, it could also be possible to reduce the high-frequency power modulation at the amplifier output, which may bring further benefits. Measurements on $CO_2$ will be presented at the conference.

## References

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