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1875-nm high-energy mode-locked thulium fiber laser

Panuwat Srisamran, Duanyang Xu, Ibrahim Abughazaleh, Matthew Gerard, Sijing Liang, David Richardson and Lin Xu

Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom

The reduced scattering at long wavelengths and transparency window of typical biological tissues means there is great interest in developing practical high energy femtosecond lasers operating in the short-wavelength infrared (SWIR) region to help increase imaging depth in nonlinear optical microscopy. The wavelength range 1800-1900 nm is of particular interest since it sits between the strong absorption peaks associated with water and lipids - two of the main components of biomedical samples [1]. Thulium (Tm) doped fiber (TDF) has an emission bandwidth that extends from ~1650 nm to 2050 nm and can be used as a gain medium for femtosecond fibre lasers. Mode locked thulium doped fiber lasers (ML-TDFLs) have been demonstrated at the short wavelength end of this emission bandwidth (e.g. at 1740 nm, albeit with a low pulse energy of 0.2 nJ [2]). Conversely, high pulse energy operation has been demonstrated at wavelengths >1900 nm (e.g. 8 nJ at 1920 nm, albeit in a cavity incorporating bulk-optic components [3]). However, the combination of operation at wavelengths in the range 1800-1900 nm and high pulse energy is challenging due to the quasi 3-level nature of TDF and the need for careful management of intracavity nonlinearity, dispersion and filtering respectively. Here we demonstrate, for the first time, a fully-fiberized ML-TDFL laser operating at 1875 nm capable of >10 nJ pulse energies.

A schematic of our mode-locked fiber laser cavity is shown in Figure 1 (a), in which a 0.65-m-length of in-house fabricated TDF with a core diameter of 8 µm and high pump absorption (~20 dB/m at 1580 nm) was used as the gain fiber [4]. The short length of TDF provides efficient gain in the SWIR region and reduces nonlinearity enabling high pulse energy operation. The TDF was pumped by an erbium doped fiber amplifier (EDFA) at 1565 nm through a wavelength division multiplexer (WDM). A semiconductor saturable absorber mirror (SESAM, SAM-1920-36-10ps from Batop Ltd) with a modulation depth of 20% was employed to realize self-start mode locking. A 5-m-length of dispersion compensating fiber (DCF, UHNA4 from Coherent Ltd) was used to manage the intra-cavity dispersion. All the fibers and components in the cavity are non-polarization maintaining (PM) except the isolator. A polarization controller (PC) was placed in front of the PM isolator to form an effective Lyot filter and thereby the filtering needed to support dissipative-soliton operation at SWIR wavelengths. The total cavity length was 11.6 m and the estimated net cavity dispersion was 0.07 ps^2.

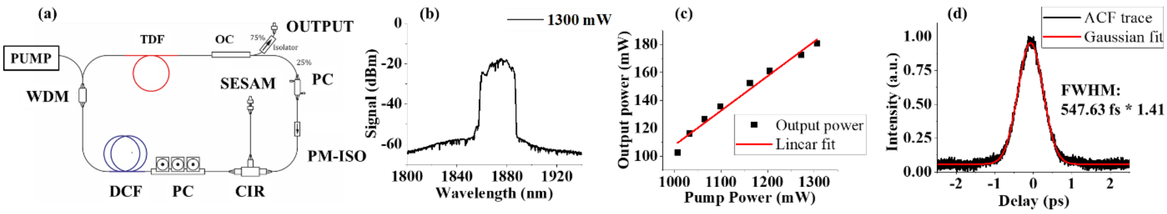

Figure 1 (a) Schematic of the laser, (b) Output spectrum, (c) Output power, and (d) Compressed pulse duration of the laser

The onset of stable single-pulse mode locking was observed at a pump powers of 1 W. The output spectrum of the pulses is shown in Figure 1 (b), which had a central wavelength of 1875 nm and a 3-dB bandwidth of 16 nm. The output power increased with pump power and reached a maximum of 180.5 mW at a pump power of 1.3 W, as shown in Figure 1 (c). At powers beyond this the mode locking became unstable. The measured pulse repetition rate was 17.5 MHz, consistent with the cavity length. The corresponding maximum output pulse energy was 10.3 nJ. The pulse duration at the output port was measured to be 12.44 ps and the pulses could be compressed down to 547.6 fs using a pair of transmission gratings with 900 lines/mm groove density, as shown in Figure 1 (d).

In conclusion, we have demonstrated a high-energy mode-locked Tm-doped fiber laser operating at 1875 nm. The laser generated pulses with a maximum pulse energy of 10.3 nJ which could be compressed extra-cavity to a duration of 547.6 fs. Our SWIR fibre laser represents a promising source for various biomedical applications.

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