Versatile mid-infrared mode-locked fiber laser, electronically tunable from 2.97 to 3.30 μm

MQ Photonics Research Centre, Macquarie University, New South Wales, Australia
robert.woodward@mq.edu.au

Abstract: We demonstrate the first dysprosium mode-locked laser: the longest wavelength and most widely tunable mode-locked fiber laser to date. Picosecond pulses are generated by a novel frequency-shifted feedback mechanism using an intracavity acousto-optic tunable filter.

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1. Introduction

The development of femtosecond and picosecond pulse sources in the near-IR (λ ~ 0.8–2.5 μm) has been a key enabling technology to a vast array of important applications, spanning research, medicine and industry. There are currently exciting opportunities for further transformative applications in the longer wavelength mid-IR region—e.g. precision spectroscopy, breath analysis and polymer processing based on strong molecular absorption features here—although this is currently held back by a lack of compact, high-performance mid-IR sources [1]. Despite significant recent progress using fluoride fibers doped with erbium and holmium, combined with semiconductor saturable absorbers (SAs) or nonlinear polarization evolution designs (NPE, employing magneto-optic isolators) to generate pulses at λ ~ 2.7–2.9 μm [2, 3], moving to longer wavelengths is a significant challenge due to material limitations. For example, 3 μm is approaching the band edge of indium-based SA materials and a lack of mid-IR compatible materials with high Verdet constant limits availability of low-loss isolators required for NPE-mode-locked ring lasers.

Here, we finally break the long-standing 3 μm barrier for mode-locked fiber laser technology by combining recently developed dysprosium (Dy)-doped fluoride fiber with a novel frequency shifted feedback (FSF) mechanism. Dy is a promising mid-IR ion, which has enabled lasing from 2.8 to 3.4 μm [4] with efficiencies exceeding 70% through in-band pumping [5], and even emission beyond 4 μm [6], but has never been considered for pulse generation. To overcome the lack of suitable SAs and low-loss magneto-optic components beyond 3 μm, we exploit a FSF technique that despite initial interest in the early days of pulsed fiber lasers [7,8], is currently understudied. Briefly, an intracavity frequency shifter monotonically shifts the wavelength of cavity light each round-trip (eventually pushing it outside the passband of an included bandpass filter), inhibiting the build-up of longitudinal mode structure and CW lasing; however, in the presence of Kerr nonlinearity, spectral components can be replenished (balancing the frequency shift effect) by self-phase modulation (SPM) of high-intensity light. By making it energetically favorable for high-intensity light, and noting that SPM-generated light is phase-coherent, a pulsed self-starting operating state is achieved [8].

2. Laser Design and Frequency Shifted Feedback Dynamics

We employ a linear cavity (Fig. 1a) including 2 m single-clad 0.2 mol% Dy:ZBLAN fiber with 12.5 μm core diameter and 0.16 NA, pumped at 2.83 μm by an Er:ZBLAN fiber laser. A dichroic mirror is butt-coupled at the input facet and an external cavity at the distal end comprises an acousto-optic tunable filter (AOTF), where the 1st order diffracted beam is resonated and the 0th order is the output. The AOTF diffraction efficiency and frequency (which sets the filter wavelength) are electronically tunable, with no moving parts. Numerical modeling is performed (based on generalized nonlinear Schrödinger equations, as described in Ref. [9]) to elucidate pulse formation seeded from shot noise through FSR dynamics. Results with an 18.1 MHz AOTF shift (corresponding to 3.1 μm filter wavelength) show the initial field build-up corresponding to temporal noise, followed by a steady shift in wavelength due to the cavity frequency shift, and finally, the growth of nonlinearly seeded (phase coherent) light to replenish shifted spectral components, forming a steady-state, corresponding to a 37 ps pulse and asymmetric spectrum (Fig. 1b).

3. Experimental Results and Discussion

The laser setup is constructed experimentally, with 18.1 MHz 1.2W RF power applied to the AOTF to maximize the cavity output power. At ~0.5 W pump power, self-starting mode-locking is observed, generating a stable pulse...
train at the fundamental repetition rate of the cavity. Remarkably, the output spectrum (Fig. 1c) shows the same characteristic features as numerical simulations: similar bandwidth with strong asymmetry, including a noticeable ‘shoulder’ (which physically relates to the steady-state energy distribution). Using an intensity autocorrelator, the pulse duration is estimated to be $\sim 33$ ps (Fig. 1d), although we note that the nature of autocorrelation measurements cannot provide the exact pulse shape (e.g. slight asymmetry is expected from the modeling). Pulse stability is excellent with an analysis of the RF spectrum revealing $>60$ dB signal-to-noise contrast. Stable operation is maintained for up to 750 mW pump power, with a slope efficiency of 40% and maximum average output power of 120 mW, corresponding to a high 2.7 nJ pulse energy. By electronically varying the RF drive frequency, the laser wavelength can be tuned from 2.97 to 3.30 $\mu$m, with stable picosecond pulsation observed at every wavelength (Fig. 1e). This significantly exceeds the current pulsed fiber laser state-of-the-art of 200 nm maximum tunability [10] and 2.9 $\mu$m longest wavelength [2].

4. Conclusion

By taking advantage of the unique spectroscopic features of dysprosium-doped fluoride glass, we have developed a versatile electronically tunable mid-IR picosecond pulse source, offering unprecedented spectral coverage. Frequency shifted feedback has also been shown to be a promising technique to overcome current limitations of mid-IR materials for pulse generation, supported by numerical modeling to reveal new insights into the pulse formation process. Work is ongoing to achieve shorter pulse durations and to apply this novel source for practical mid-IR gas-sensing applications.

References