2-µm energy-managed soliton fiber laser

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1. Introduction

Thulium-doped fiber lasers are prized for their broadband gain, power scalability, and efficiency. They find applications in remote sensing, lidar, telecommunications, as well as in surgery, urology, dermatology, and ophthalmology, due to their strong absorption in water [1,2]. However, the large anomalous dispersion of silica in the 2-µm wavelength region typically confines mode-locked lasers to the conventional soliton regime [3,4]. Low-loss normal-dispersion silica fibers are more difficult to engineer at 2 µm than at 1.5 µm. Efforts to incorporate normal dispersion Tm-doped fibers or dispersion compensation fibers (DCF) in lasers yielded either sub-nJ pulses [5], or nJ pulses (~ 4.5 nJ) but with significant chirping and undesired spectral shapes [6]. Here, we develop a fiber cavity architecture implementing energy management and spectral filtering [7]. It generates multi-nJ ~1-ps pulses through limiting the amount of self-phase modulation and suppressing undesired dispersive waves. Energy management involves both low and high energy pulse propagation sections in the fiber cavity, with an energy contrast close to 20 dB. In the low energy section, close to fundamental (N=1) solitons propagate with minimum distortion, whereas the short high-energy section includes a high-gain optical fiber to output high-energy pulses. We demonstrate the generation of neat waveforms and high-energy pulses (~12 nJ) using standard telecom fiber components, directly from the fiber oscillator. Additionally, our laser offers an advantageous flexibility, allowing a wide tunability of the repetition rate and of the central wavelength of mode-locked pulses.

2. Results

The laser cavity depicted in Fig. 1a illustrates the configuration of the energy-managed soliton fiber laser operating at around 2 µm. It is a unidirectional ring laser mode locked through nonlinear polarization evolution (NPE). A thulium-doped fiber (TDF) acts as the gain medium within the 1750 - 2100 nm lasing window in the anomalous dispersion regime. It is pumped at 1567 nm by a 5 W laser source coupled through a wavelength-division multiplexer (WDM). At the output of the TDF, the laser field is decoupled into free space, allowing precise polarization control and NPE discrimination via wave plates and a polarizing beam splitter (PBS). The PBS rejection port serves as the primary laser output, extracting over 85% of intracavity power as high-quality pulses. It is followed by a polarization wave plate to adjust the nonlinear transfer function and a grating. Recoupling the laser light into a standard single-mode fiber (SMF) after experiencing spatial dispersion by the grating achieves spectral selection, facilitating tuning of the central wavelength. The rest of the cavity consists of a 10% coupler and a polarization-insensitive isolator (PI-ISO) to ensure unidirectional lasing. Subsequent propagation in the SMF fiber occurs at reduced optical peak power comparable to that of a conventional fundamental (N=1) soliton, offering flexibility in the length of SMF used.

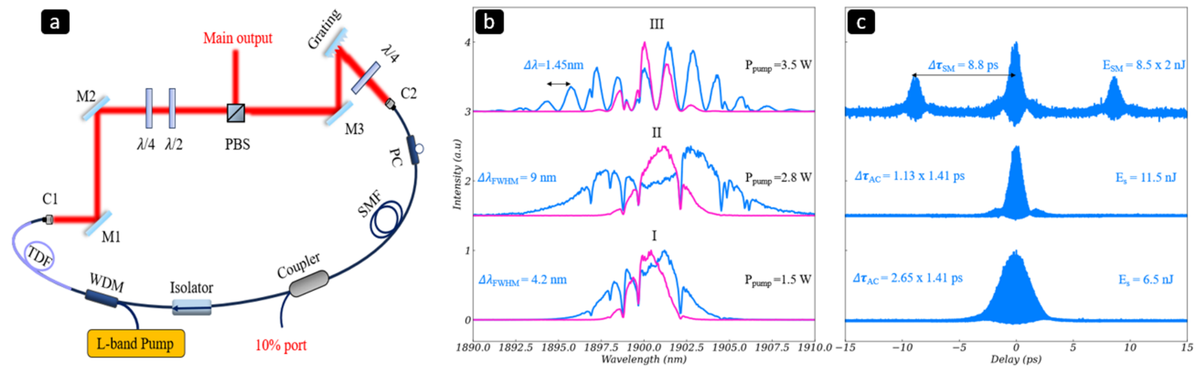

Figure 1: 2-µm energy-managed soliton fiber laser. (a) Schematic of the experimental mode-locked fiber laser cavity. WDM: wavelength division multiplexer, (TDF): thulium-doped gain fiber, (c1, c2): collimators, (M1-M3): mirrors, (λ/2, λ/4): half and quarter waveplates, (PBS): polarizing beam splitter, (PC): polarizer controller. (b) and (c) are the spectra and autocorrelation traces of various mode-locked regimes with the main (PBS) laser output in blue color and the spectra from the secondary (10%) output in pink color.

At a 27.6-MHz fundamental repetition rate, by setting the orientations of the wave plates and the grating, reproducible self-starting mode-locking regimes are obtained, see Fig. 1(b, c). The mode-locked regimes (I and II) in Fig. 1(b, c) are classified according to the accumulated nonlinear phase ϕ_{NL}. The region (I) defines sech-profiled pulses devoid from Gordon-Kelly sidebands and are associated with ϕ_{NL} below 2π and peak power below 3 kW. Region (II) is obtained at a higher pump power and tolerates a large accumulated nonlinear phase (2π <

$\phi_{NL} < 10\pi$) deduced from the spectral broadening shown in Fig. 1b at peak power values that goes up to 10 kW for the running intracavity pulse. A further increase of the pump power will lead to multi-pulse regimes (III), such as soliton molecule generation shown on the top curves of Fig. 1(a, b).

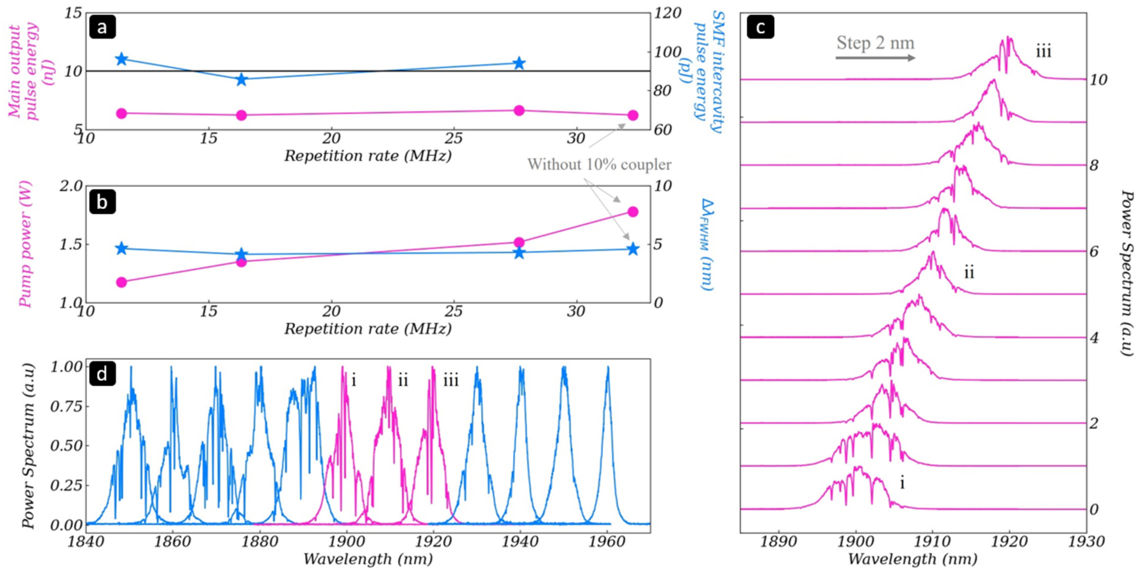

Figure 2: Laser flexibility over the repetition rate and central wavelength. (a) Main and 10% laser output energies vs repetition rate. (b) Pump power and spectral width vs repetitio rate. (c) Continuous fine-tuning of the laser wavelength over 20-nm through the grating orientation, keeping all other laser parameters identical. (d) Wide span ~ 120nm of the generated mode-locked pulse involving tuning of both the grating orientation and alignment of the coupling lens.

The energy management not only allows for higher pulse energy but also for repetition rate flexibility, as shown in Fig. 2(a,b). Mode locking persists even with additional SMF lengths up to 50 meters, maintaining consistent pulse outputs of approximately 6 nJ with the same mode-locked pulse characteristics, allowing an interesting downscaling of the pump power as the repetition rate decreases. Another flexibility is given by the grating, which allows a wide range of central wavelength tuning. Starting at 1900 nm, continuous tuning of the mode locking over a 20 nm window is achieved by changing solely the grating orientation, with recorded spectra every 2 nm (see Fig. 2c). This procedure is extended over a 100 nm span, requiring slight realignment of the lens coupled to the SMF (see Fig. 2d) with recorded spectra every 10 nm.

3. Conclusion

We have proposed and experimentally validated a mode-locked fiber laser operating around the 2-µm wavelength window using standard telecom fiber components working in an all-anomalous dispersion regime. This laser generates high pulse energy, two orders of magnitude higher than conventional solitons propagating along the cavity assuming the same pulse duration. The designed laser exhibits an exceptional flexibility over the mode-locked pulse's central wavelength and enables the generation of more complex pulse structures at higher pump power, involving soliton molecule dynamics. Further details regarding the prospective scaling of pulse energy, confirmed by numerical simulation, and potential applications will be provided at the conference.

4. References

[1] S. W. Henderson, P. J. M. Suni, C. P. Hale, S. M. Hannon, J. R. Magee, D. L. Bruns, and E. H. Yuen, Coherent laser-radar at 2 m using solid-state lasers, IEEE Trans. Geosci. Remote Sens. **31**, 415 (1993).

[2] G. Huttmann, C. Yao, and E. Endl, New concepts in laser medicine: towards a laser surgery with cellular precision, Med. Las. Appl. **20**, 135139 (2005).

[3] Nelson, L. E., Ippen, E. P. & Haus, H. A. Broadly tunable sub-500 fs pulses from an additive-pulse mode-locked thulium-doped fiber ring laser. Appl. Phys. Lett. **67**, 19–21 (1995).

[4] Wang, Q., Geng, J., Jiang, Z., Luo, T. & Jiang, S. Mode-locked Tm–Ho-codoped fiber laser at 2.06 µm. IEEE Photon. Technol. Lett. **23**, 682–684 (2011).

[5] Haxsen, F., Wandt, D., Morgner, U., Neumann, J. & Kracht, D. Monotonically chirped pulse evolution in an ultrashort pulse thulium-doped fiber laser. Opt. Lett. **37**, 1014–1016 (2012).

[6] Huang, C., Wang, C., Shang, W. et al. Developing high energy dissipative soliton fiber lasers at 2 micron. Sci. Rep. **5**, 13680 (2015).

[7] M. I. Mohamed, A. Coillet, and P. Grelu "Energy-managed soliton fiber laser," Europhoton 2024 submitted paper No. 87.