Extreme ultrafast pulsation in Tm/Ho mode-locked linear cavity fiber lasers

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Abstract: In a Tm/Ho-doped ultrafast linear cavity fiber laser, extreme optical pulsation is demonstrated. Single-pulsing behavior at the fundamental repetition rate is maintained while the level of chaotic pulsation is adjusted by an intracavity polarization controller.
OCIS codes: (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (190.5530) Pulse propagation and temporal solitons.

1. Introduction

Numerous intriguing nonlinear and ultrafast phenomena have been explored in passively mode-locked fiber lasers. Beyond conventional solitonic ultrafast pulsation with equal pulse intensities, several pathways have been proposed for observing exotic pulsing regimes, including e.g. noise-like pulses, rogue waves and soliton explosions [1,2]. Ultrafast pulses can be manipulated by exploiting one or more of the governing effects for mode-locking, e.g. dispersion, nonlinearities, gain and loss dynamics. If additional intracavity power is present beyond the soliton energy quantization at the fundamental repetition rate, shedding of the additional energy and relaxation oscillations can impact the mode-locked fiber laser performance, yielding spectral and temporal changes such as the generation of additional sidebands, strong amplitude fluctuations and transitional states [3,4]. In this study, we present a unique pathway to generate extreme ultrafast pulsation in a compact linear cavity fiber laser configuration without any additional nonlinear cavity element that can be an intriguing candidate for a better exploration of the complex underlying physics of chaotic pulsing regimes.

2. Experimental Results and Discussions

The fiber laser configuration is core-pumped with a 790 nm cw laser, see Fig. 1(a) (compare [5]). The gain medium is a single-mode, single-cladding thulium/holmium (Tm/Ho) co-doped fiber (TH512 from Coractive), which is characterized by a peak absorption of 120 dB/m at the pump wavelength. The linear cavity consists of 70 cm of gain fiber. One end is spliced to 5 cm of SMF-28e+ and coupled to a saturable Bragg reflector (SBR, from BATOP GmbH). For the chosen gain fiber length, reabsorption effects in the gain medium are expected. A 10% output coupler (OC) is butt-coupled to the other end of the cavity. The pump and the laser light are separated with an external dichroic mirror (DM). The laser operates in a soliton mode-locking (ML) regime while the net birefringence of the cavity is modulated with an inline polarization controller.

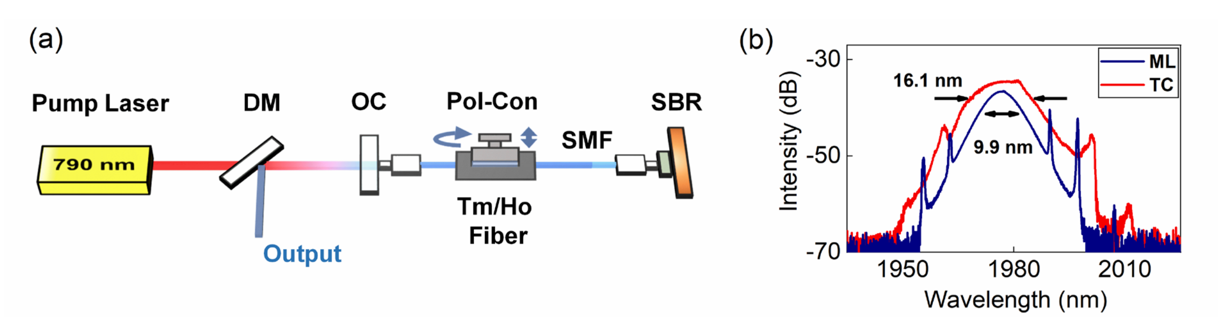

Fig. 1. (a) Soliton mode-locked Tm/Ho doped linear fiber laser configuration, (b) the optical spectrum for the single pulsing mode-locking (ML) and the transitional chaotic (TC) state.

Single pulsing ML operation is achieved for coupled pump power values between 90 mW and 115 mW at a repetition rate of 135.2 MHz. The average output power ranges from 5 mW to 7.3 mW, corresponding to intracavity pulse energies of 37 pJ and 54 pJ, respectively. For specific polarization controller settings, the laser produces 2nd order harmonically ML (HML) states when the pump power exceeds 180 mW. At the 2nd order HML threshold an average output power of 10.1 mW is generated, yielding pulse energies of 37.5 pJ corresponding nicely to twice the minimum soliton pulse energy. As can be deduced from the lower and higher bounds of the sustained pulse energies, the cavity experiences a transitional condition where the intracavity power is insufficient to support multiple pulses in one round trip but has a surplus energy for single pulsing ML. Thus, for output power levels between 7.3 mW to 10 mW, transitional chaotic (TC) states are observed based on single pulsing ML operation driven with random amplitude fluctuations. The optical spectrum for the single pulsing ML and TC states is shown in Fig. 1(b). For intracavity pulse energies of 50 pJ, single pulsing ML is characterized by a conventional sech shaped spectrum centered at 1970 nm with a full width half maximum (FWHM) of 9.9 nm, corresponding to a transform-limited pulse duration of 410 fs. The optical spectrum dramatically changes to a flatter top profile for the transitional state for an output power of 95 mW. The FWHM is measured as 16.1 nm for the transitional state, while it should be noted that the spectrum deviates from the sech shaped profile.

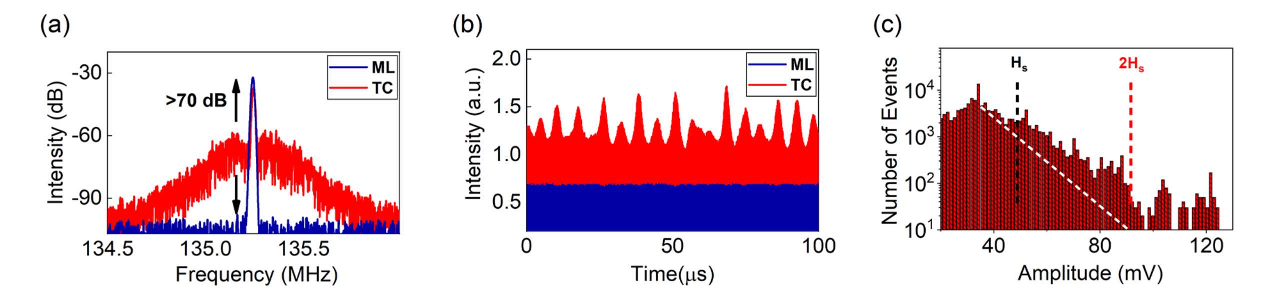

Fig. 2. (a) The fundamental peak radio frequency (RF) spectrum of the single pulsing ML and TC states. (b) Long term oscilloscope traces of ML and TC states (intentionally offset in intensity). (c) Distribution of the pulse energies in the TC state, showing extreme optical pulsation due to the generation of pulses with energies exceeding twice the significant wave height (H_s).

Fig. 2(a) shows the fundamental peak RF spectrum of the single pulsing ML and TC states. The fundamental RF peak of TC state features a wider and noisier spectrum compared to single pulsing ML state. The noisy pedestal of the fundamental RF peak has a single sided FWHM of 95 kHz, while the 40 dB signal to noisy pedestal ratio hints at continuing uninterrupted ultrafast pulse generation. The long-term oscilloscope traces of ML and TC states are shown in Fig. 2(b) for a time interval of 100 µs, where the TC state features strong amplitude fluctuations on top of the constant ultrafast pulse train. In order to confirm the generation of extreme optical pulsation, the statistical analysis of the TC state is shown in Fig. 2(c). The histogram of the amount of events with respect to their amplitudes for more than $2 \cdot 10^6$ pulses features a strong deviation from the classical distribution (shown as the white dashed line). Further, the extreme pulsation is also confirmed with the generation of pulses more energetic than the conventional figure of merit in defining the rogue behavior for optical or ocean waves (shown as the red dashed line), two times of the significant wave height (H_s).

3. Conclusions

Transitional chaotic states are investigated in a mode-locked Tm/Ho doped fiber laser featuring extreme ultrafast pulsation for the first time in a linear cavity configuration. If the intracavity power fall within a range that is insufficient for multiple pulse generation, it produces single pulsing operation with shedding of energy, resulting in random amplitude fluctuations. This unique state offers an intriguing platform for the exploration of the underlying physics of chaotic ultrafast pulsation in a compact mode-locked fiber laser configuration.

4. References

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