# Scaling of High Repetition Rate Mode-Locked Tm-doped Fiber Lasers

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**Abstract:** Scaling of a compact linear soliton mode-locked Tm-doped fiber lasers with repetition rates of 531.9 MHz, 704.3 MHz, and 969.0 MHz with transform limited pulse durations down to 358 fs is demonstrated.
**OCIS codes:** (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (320.7090) Ultrafast lasers

## 1. Introduction

High repetition rate thulium (Tm)-doped fiber lasers with femtosecond pulses are attractive for applications such as high speed optical sampling, frequency metrology or optical arbitrary waveform generation. While harmonic mode-locking and external repetition rate multiplication can form a pathway towards high repetition rates, the stability and noise properties of fundamentally mode-locked lasers are usually desirable properties. To achieve GHz repetition rates or higher through reducing the fiber cavity length, highly doped gain fiber integrated into compact laser designs are needed that can support the necessary nonlinearities to generate femtosecond pulses. Thus, to date, passively mode-locked high repetition rate Tm-doped fibers have been demonstrated with custom-made gain fibers and customized components, up to repetition rates of 1.6 GHz [1], 982 MHz [2] and 535 MHz [3]. To our best of knowledge, this is the first time that a systematic scaling of Tm mode-locked lasers reporting repetition rates up to 1 GHz based on commercially available components and gain fiber is demonstrated and their performance fully characterized. In this work, lasers with a fundamental repetition rate of 531.9 MHz, 704.3 MHz, and 969.0 MHz are presented where the mode-locking threshold is set at similar soliton pulse energies, providing a pathway to scale the repetition rate while maintaining comparable optical performance.

## 2. Experimental Results and Discussions

For a compact cavity, a linear soliton mode-locked configuration is designed, as illustrated in Fig. 1(a). Three cavities with lengths of 19.2 cm, 14.5 cm, and 10.5 cm are all composed of a 7 cm long single-mode Tm-doped fiber piece (Nufern, SM-TSF-5/125) that is spliced to varying lengths of 12.2 cm, 7.5 cm, and 3.5 cm of single-mode fiber SMF-28e+ correspondingly. The passive fiber end of the cavity is butt-coupled to a saturable Bragg reflector (SBR, BATOP GmbH), and the other end is coupled to a 10% output coupler. An external dichroic mirror is used to separate the pump and output light. The laser is core-pumped at a wavelength of 1565 nm. All three laser configurations feature a net anomalous cavity dispersion.

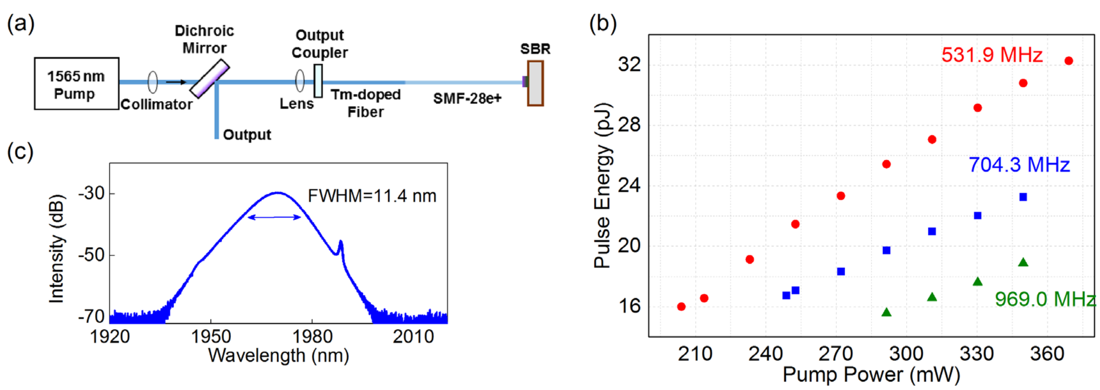


Fig. 1. (a) Schematic of a soliton mode-locked fiber laser configuration with varying cavity lengths for high repetition rates. (b) The mapping of the pulse energy with regards to the coupled pump power indicates that similar soliton energies are required to initiate mode-locking. (c) Optical spectrum of one of the shortest pulse achieved with FWHM of 11.4 nm at repetition rate of 704.3 MHz.

The laser with a 19.2 cm-long cavity at a repetition rate of 531.9 MHz generates single pulsed mode-locking with an average output power of 7.0 mW for a coupled pump power value of 204 mW. The corresponding intracavity pulse energy is 16 pJ, which is comparable to the mode-locking threshold of the other two lasers. As shown in Fig. 1(b), the pulse energy increases from 16 pJ to 32 pJ (corresponding to 13.9 mW of output power) linearly with the coupled pump power. For a pulse energy of 17 pJ, the average output power of the 531.9 MHz laser is measured to be 7.1 mW. Based on this value, the output power for the 704.3 MHz and 969.0 MHz laser for the same pulse energy is predicted as 9.4 mW and 12.9 mW, which corresponds well to the measured output power of 9.5 mW and 13 mW, respectively. Pulses with a transform limited pulse duration down to 358 fs can be achieved with the 704.3 MHz laser, see Fig. 1(c).

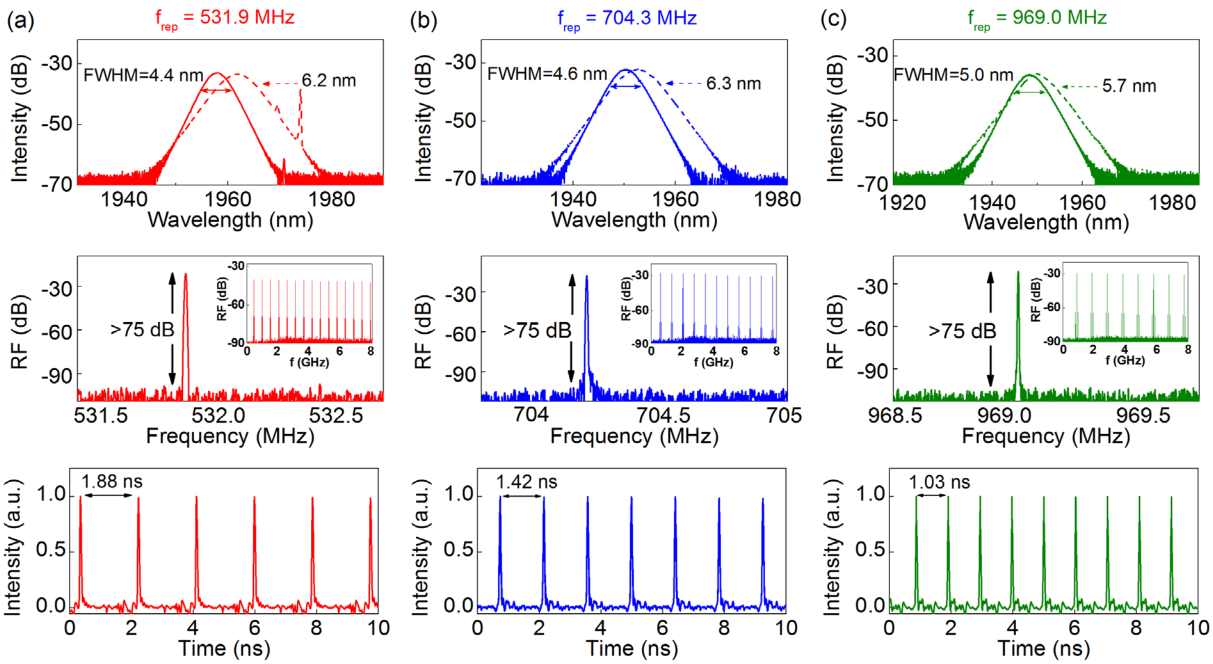


Fig. 2. (a), (b), and (c) correspond to the 531.9 MHz, 704.3 MHz, and 969.0 MHz repetition rate laser, respectively. Top row: The optical spectrum is measured at the mode-locking threshold (solid line) and for the highest measured pulse energy (dashed line). Middle row: RF spectrum of the fundamental repetition rate, and the insets show the RF spectral traces for a 8 GHz-span. Bottom row: Measured oscilloscope traces.

The performance of three lasers are studied systematically at comparable center wavelengths. As shown in the top row of Fig. 2(a), (b), and (c), the lasers operate at a center wavelength of 1958 nm, 1950 nm, and 1948 nm at the mode-locking threshold, respectively. As pump power increases, the pulses are red-shifted and gain a larger optical spectral bandwidth. For the particular states chosen, the full width at half maximum (FWHM) varies between 4.4 nm and 6.3 nm, corresponding to transform-limited pulse durations from 914 fs to 638 fs. The signal-to-noise ratio of the fundamental RF peak, as shown in the middle row of Fig.2, is greater than 75 dB (resolution bandwidth of 5 kHz), indicating high noise suppression. The stability of all three configurations is confirmed by the RF spectral trace, shown as insets. The oscilloscope traces (last row Fig. 2) feature uniform pulse trains with pulse spacings of 1.88 ns, 1.42 ns, and 1.03 ns, respectively, corresponding to the measured repetition rates.

## 3. Conclusion

We demonstrated a linear Tm-doped femtosecond fiber laser with a scalable fundamental repetition rate from ~0.5 GHz to ~1 GHz. For the same gain fiber lengths, the soliton energy required for mode-locking features a similar threshold, enabling repetition rate and output power scaling. Given the comparable laser performance of all three cavities, it is projected that lasers with similar performance with repetition rates over 1 GHz can be achieved by shortening the cavity length further.

## 4. References

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