



20 GHz actively mode-locked thulium fiber laser

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Abstract: A high repetition-rate actively mode-locked thulium fiber laser is demonstrated where an electro-optic lithium niobate phase modulator is used to synchronize the longitudinal modes in the cavity. The repetition rate of the actively mode-locked laser is tunable from 14.6 MHz to 19 GHz, where the 19 GHz pulses exhibit a super-mode suppression ratio of 46 dB. Furthermore, the output pulse width could be manipulated through finely controlling the detuning frequency or repetition rate. We have also experimentally observed rational harmonic mode-locking in the laser and obtained 14 GHz and 21 GHz repetition rate pulses using a 7 GHz modulating signal. To the best of our knowledge, we have improved the repetition-rate of actively mode-locked thulium fiber laser by more than one order of magnitude. Such a high repetition source can be readily synchronized to a master clock, which makes it very suitable for high speed optical data processing, communication and remote sensing.

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1. Introduction

Mode-locked lasers operating at the eye-safe 2 μm region have attracted intense attention for several potential applications in medical surgery, LIDAR, material processing and remote sensing [1–5]. The broad amplification bandwidth of thulium-doped (Tm-doped) silica fiber lasers, ranging from 1.8 to 2.1 μm , makes them very suitable for wideband wavelength tuning and ultrashort pulse generation. For example, an ultra-broad tuning range of 200 nm was achieved in a carbon nanotube mode-locked laser [6]. Besides, ultrashort mode-locked Tm-doped fiber lasers have been successfully developed by several novel saturable absorption

materials like graphene, topological insulator, black phosphorus and etc [7–13]. While most of these lasers are working at a repetition rate of tens of megahertz. 2 μm pulsed lasers with tens of gigahertz repetition rates are still lacking behind compared with the conventional band at 1.5 μm [14–19], which are attractive for realizing high capacity telecommunication and data processing [20–23].

High repetition rate pulsed laser can be realized through extra-cavity modulation, gain switching, passive harmonic mode-locking and active mode-locking. Recently, a 6 GHz picosecond laser at 2 μm was realized by employing spectrally masked phase modulation (SMPM). This modulation technique has the advantage of generating pulses without the need for a resonant cavity, therefore enhancing stability and flexibility [24,25]. Gain switched semiconductor laser diode exhibit excellent wavelength and temporal flexibility. However, constrained by the average power of the diode laser, the output pulse energy and peak power is very low (pulse energy: 66.7 fJ, peak power: 19.05 mW), which needs to be amplified for practical applications. The amplified spontaneous emission noise during power amplification must be carefully managed and the experimental structure is complex [26]. The repetition-rate of passively mode-locked fiber lasers is always limited by the relatively long cavity length, because enough active fiber must be used to provide sufficient gain for lasing. Although passively harmonic mode-locked lasers with gigahertz repetition rate have been reported, these systems always sustain low super-mode suppression and poor timing jitter [27–29]. Ultra-short laser cavity structure is an alternative for increasing the repetition rate, however, the fundamental repetition rate was limited to 1.6 GHz at 2 μm thus far [30,31]. Active mode locking is an excellent scheme for generating high repetition rate pulses by modulating the cavity loss or phase periodically through an intra-cavity electro-optic modulator at a harmonic cavity frequency. A phase modulator is more attractive than an intensity modulator, since it has no DC bias, relegating effects from the DC bias drift of the modulator. The actively mode-locked (AML) fiber lasers can run at hundreds or even thousands of times of the longitudinal mode spacing (fundamental cavity frequency). By this technique, tens of GHz lasers have been achieved at 1.5 μm [17]. The first AML Tm-doped fiber laser was reported in 2011 by using an acousto-optic modulator, but the laser can only operate at the fundamental mode-locked regime [32,33]. Yin et al. reported a 1.5 GHz Tm-doped AML fiber laser with an electro-optic intensity modulator driven by electrical pulses in 2014 [34]. To the best of our knowledge, further scaling of the repetition rate of AML laser at 2 μm region has not been reported.

In this letter, we developed a high repetition rate AML Tm-doped fiber laser. The laser is mode locked by driving a lithium niobate phase modulator with a RF signal equal to integral multiples of the longitudinal mode spacing. The repetition rate can be turned from 14.6 MHz to 19 GHz by adjusting the RF driving signal. The super-mode suppression ratio for the 19 GHz pulse train was measured to be 46 dB. The pulse width of the AML pulses can be tuned by changing the detuning frequency and repetition rate. Moreover, we also experimentally observed the phenomenon of rational harmonic mode-locking (RHML) at 2 μm and obtained 14 GHz and 21 GHz repetition rate pulses when the RF modulation frequency was set to 7 GHz. The 21 GHz pulses have a measured super-mode suppression ratio of 39 dB.

2. Experimental setup

The schematic experimental setup of the AML laser is shown in Fig. 1. The pump source is provided by a laser diode (LD) operating at 1550 nm. The LD has an average output power of 10 mW and is subsequently amplified by a commercial erbium-doped fiber amplifier (EDFA). The pump laser is launched into the ring cavity through a 1550/2000 nm wavelength division multiplexer (WDM). 3 m long single mode Tm-doped fiber (Coractive Inc., TH512) with core/cladding diameters of 9/125 μm and numerical aperture of 0.16 was used as the gain medium. The core absorption of the fiber is measured to be 13 dB/m at the pump wavelength of 1550 nm. A polarization sensitive lithium niobate phase modulator with 10 GHz bandwidth

(LNPM, EOSPACE Inc.) is used in the cavity to initiate active mode-locking. In order to optimize the transmission of the phase modulator, we introduce a polarization controller (PC) to control the polarization state of the incident light as well as the mode-locking performance. An isolator is inserted in the cavity to ensure unidirectional running of the laser. Output pulses are extracted from the cavity by a 30:70 optical coupler (OC). The total cavity length of the laser is about 14.25 m, corresponding to a longitudinal mode spacing of $\Delta\nu = c/nL = 14.6$ MHz.

The LNPM is driven by a sinusoidal RF signal generator (Keysight Inc., N5183) with frequency up to 20 GHz. The RF signal is then amplified to a saturated output power of 27 dBm to satisfy the power requirement of the LNPM. A diagnostic part is introduced for synchronous and real-time monitoring the output characteristics of the AML Tm-doped fiber laser. Firstly, the output of the laser is separated by a 40:60 output coupler. 40% of the power is used to monitor the optical spectrum by an optical spectrum analyzer (Yokogawa Inc., AQ6375). The resolution of the optical spectrum analyzer is 0.05 nm. The remaining part is detected by a high speed photodetector with a nominal bandwidth of 22 GHz (Discovery Semiconductor Inc. rise time < 16 ps). The detected signal is then split by a 50:50 RF splitter (Mini Circuits Inc.) to monitor the pulse trains and RF spectrum by a 33 GHz real-time digital oscilloscope (Keysight Inc., MSOV334A) and a RF spectrum analyzer (R&S Inc. FSV 30).

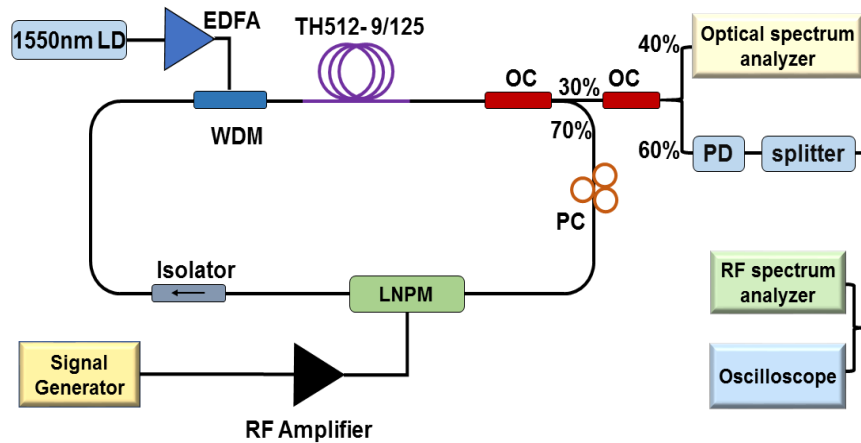


Fig. 1. The schematic of the AML fiber laser system. LD: laser diode; EDFA: erbium-doped fiber amplifier; OC: optical coupler; PC: polarization controller; LNPM: lithium niobate phase modulator; PD: photodetector.

3. 19 GHz active mode-locking

Both fundamental and harmonic AML pulses can be obtained in the experiment. First, the RF driving signal was set to 14.6375 MHz to match the longitudinal mode spacing. Further, high order harmonic mode-locked pulses were obtained by increasing the frequency of the RF signal to be integral times of the cavity frequency. In the meanwhile, the power of pump light and RF signal were increased to ensure the stability of the pulses. Figure 2 shows the AML pulses running at repetition rates of 14.6 MHz, 6 GHz, 15 GHz, and 19 GHz, corresponding to the 1st, 411th, 1027th and 1301th order cavity harmonics.

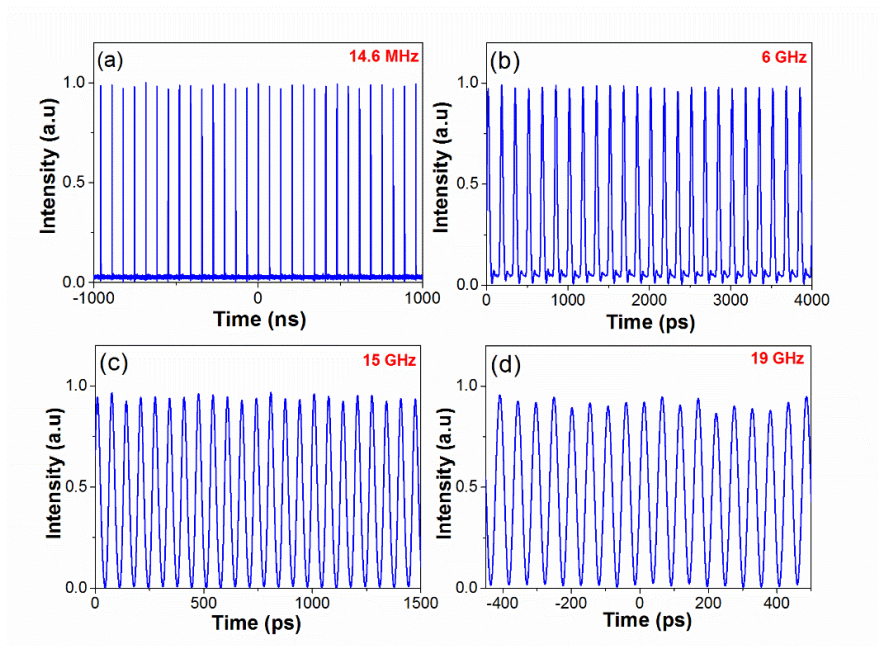


Fig. 2. The mode-locked pulse trains observed by a real-time oscilloscope for (a) 14.6 MHz, (b) 6 GHz, (c) 15 GHz and (d) 19 GHz.

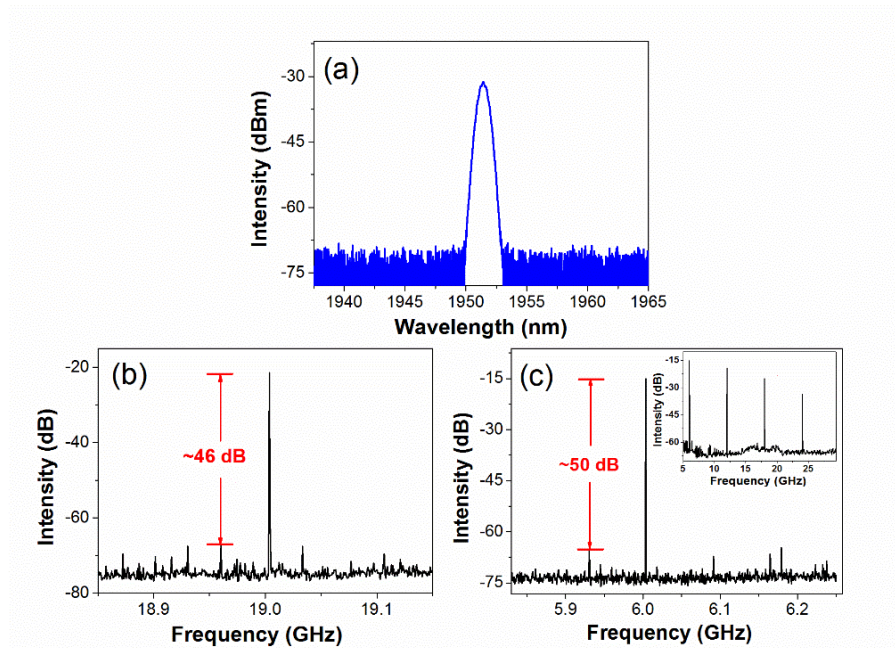


Fig. 3. Output characteristics of the AML Tm-doped fiber laser. (a) Optical spectrum, (b) the RF spectrum of the 19 GHz pulses observed by a RF spectrum analyzer (RBW: 2 kHz) and (c) RF spectrum of the 6 GHz pulse 6 GHz (inset: RBW: 20 kHz, scan range: 25 GHz).

The highest repetition rate pulses at 19 GHz has an output power of 30 mW under the pump power of 591 mW. The corresponding optical spectrum and RF spectrum were recorded at the same time as shown in Figs. 3(a) and 3(b). The optical spectrum is centered at 1951.5 nm with

a 3 dB bandwidth of 0.72 nm. The RF spectrum of the detected pulses in Fig. 3(b) exhibits a super-mode suppression ratio of 46 dB under a resolution bandwidth (RBW) of 2 kHz. As a matter of fact, higher super-mode suppression can be observed at lower repetition rate. For instance, the super-mode suppression ratio of 6 GHz mode-locked pulses is more than 50 dB in Fig. 3(c). This degradation of the mode suppression towards the high repetition rate is due to the electrical bandwidth (10 GHz) of the LNPM. On the other hand, although higher pump power and RF power is preferred for better super-mode suppression ratio, it may increase the risk of damaging the LNPM. We assume that the situation would be greatly improved by employing a higher speed LNPM. However, the super-mode suppression ratio during the whole mode locking range is still acceptable for practical applications. Besides, the timing jitter of the 19 GHz AML pulses is estimated to be ~ 7.8 ps, which is measured by the timing jitter measurement model (EZJIT +) of the oscilloscope.

Figure 4(a) recorded the average output power with respect to incident pump power. The system started lasing action at a pump power of 280 mW. The slope efficiency of the pulses changes slightly from 8.7% to 9.8% under different repetition rates (14 MHz-15 GHz). This difference is attributed to the polarization-sensitive phase modulator as we slightly adjust the polarization state to optimize the mode-locking performance. It is obvious to see that there is no direct relationship between the lasing slope efficiency and repetition rate. On the other hand, we also noted the pump threshold power for stable active mode locking at 1, 6, 8, 10, 12, 14, 17 and 19 GHz. The corresponding pump powers are 309, 312, 315, 317.5, 326, 335.1, 350 and 361 mW, respectively. It is clearly observed in Fig. 4(b) that the pump threshold power is increasing from fundamental mode-locked frequency towards higher repetition rate. This is mainly due to the pulse energy decreases with the increasing of repetition rate. Therefore, much more pump power is needed to sustain higher repetition rate active mode locking.

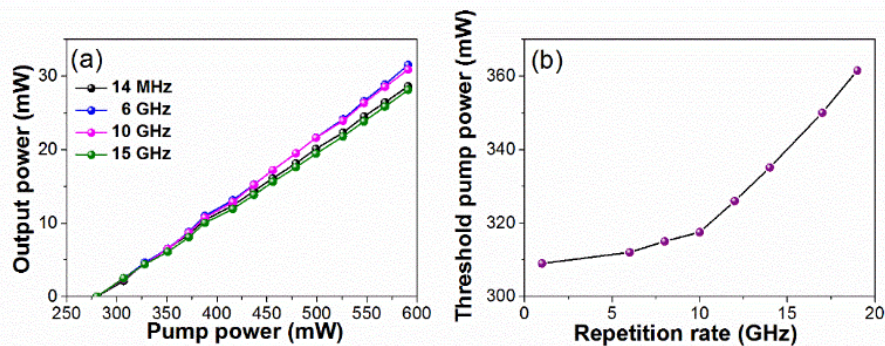


Fig. 4. (a) Average output power with respect to incident pump power at 14 MHz, 6, 10, 15 GHz. (b) Pump threshold power for stable AML pulses for different repetition rates.

The pulse width of AML laser is an important figure-of-merit for practical applications. However, autocorrelation trace cannot be obtained due to the very low peak power and high repetition rate of the pulses, so we use the 33 GHz oscilloscope (rise time < 13.3 ps) to record the pulse width. The effect of small detuning between the modulation frequency and longitudinal mode spacing has been theoretically and experimentally studied in AML erbium-doped fiber lasers and AML semiconductor lasers [35]. Here we also investigated this effect in our AML Tm-doped fiber laser. The result is shown in Fig. 5(a). We find that the pulse width of the mode locked laser increases while we detune the RF signal away from the cavity frequency (from f_0 to $f_0 + 5$ kHz, 10 kHz, 15 kHz, 20 kHz, 25 kHz, 30 kHz). The detuning will result in a drift between the optical pulses and the RF modulating signal in LNPM. It is shown in Fig. 5(b) that there is a linear relationship between the pulse widths versus detuning frequency. In our experiment, the pulse width of the AML pulses can be linearly regulated from 311 ps to 1 ns by finely the detuning. Besides, we also investigated the

pulse width of the AML laser under different mode-locked repetition rates. Figure 5(c) depicts that the pulse width decreases from 105.16 ps to 26.5 ps as the repetition rate increases from 400 MHz to 19 GHz in our AML laser system. Actually, the pulse width of the 19 GHz pulses displayed on the oscilloscope is larger than the transform limit width due to the limited bandwidth of the oscilloscope and photodetector. However, this limitation does not affect the tendency between pulse width and repetition rate. Accordingly, the pulse width was found to be inverse proportional to the square root of the repetition frequency as shown in Fig. 5(d), which is similarly to conventional mode-locked fiber lasers [35,36].

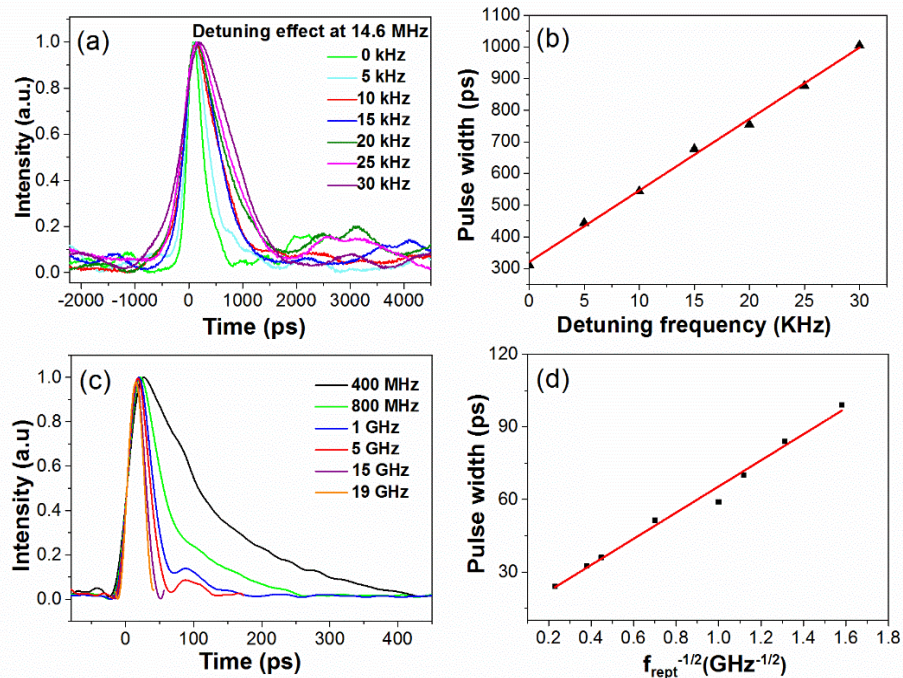


Fig. 5. (a) Different pulse widths under detuning frequencies (0 kHz, 5 kHz, 10 kHz, 15 kHz, 20 kHz, 25 kHz, 30 kHz). (b) The relationship between detuning frequency and pulse width; (c) Different pulse widths at several repetition rates. (d) Linear relationship of the pulse width with respect to the reciprocal square root of the repetition rate.

4. 21 GHz rational harmonic mode-locking

RHML can take place in an AML laser where an optical pulse train with a repetition rate of $(np + 1)f_l$ can be produced when the modulation frequency is set to $(n + 1/p)f_l$, where f_l is the longitudinal mode spacing, p and n are integral numbers. In other words, the output pulses can operate at a repetition rate of p ($p = 2, 3, \dots$) times of the RF modulation frequency [35–38].

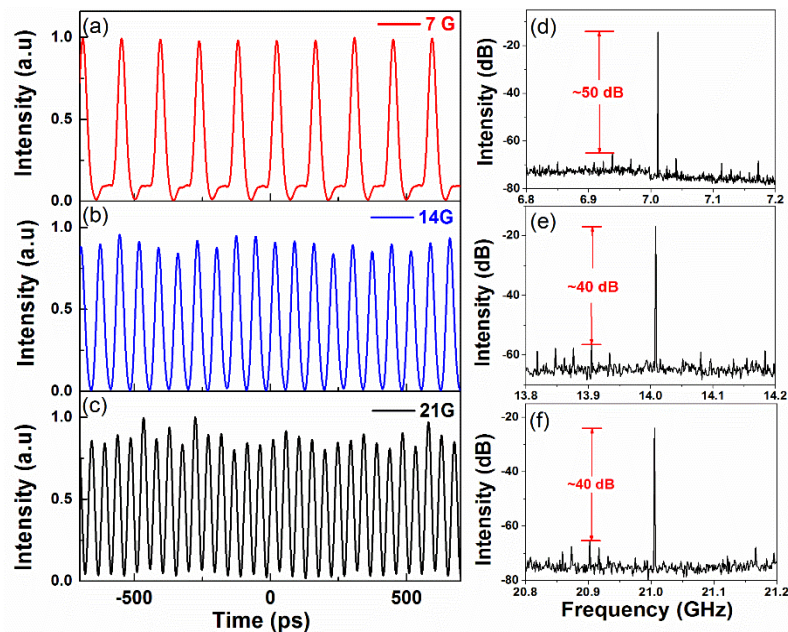


Fig. 6. Output pulse trains of RHML laser with repetition rate of (a) 7 GHz, (b) 14 GHz, (c) 21 GHz and the corresponding RF spectra (e-f).

Drawing on this effect, 7 GHz, 14 GHz and 21 GHz repetition rate pulses were obtained when the RF modulation frequency were set at 7.008 GHz ($n = 480, p = 0$), 7.0153 GHz ($n = 480, p = 2$) and 7.0128 GHz ($n = 480, p = 3$), respectively. The pulse trains are shown in Figs. 6(a)-6(c). It should be noted that these three repetition rates were obtained under the same conditions except the RF modulation frequency. The power of the RF modulation signal is kept under 27 dBm and the pump power is kept at 603 mW. Figures 6(d)-6(f) illustrate the RF spectra of the RHML pulses. The measured super mode suppression ratio of 7 GHz, 14 GHz and 21 GHz mode-locked pulses are 50, 40 and 40 dB, respectively. The optical spectrum of the RHML pulses at 21 GHz is centered at 1951.74 nm with a 3 dB bandwidth of 0.64 nm. RHML pulses with much higher repetition rate can still be possible in our system, but now it is limited by the bandwidth of our photodetector. Actually, rational harmonic mode-locking can be experimentally observed under other modulation frequencies.

5. Conclusion

In conclusion, an actively mode-locked Tm-doped fiber laser based on lithium niobate phase modulator was investigated experimentally. The repetition rate can be turned from 14.6 MHz to 19 GHz by simply adjusting the RF driving signal. The super-mode suppression ratio for the 19 GHz pulse train was measured to be 46 dB. This is the highest repetition rate that has been reported for actively mode-locked fiber laser at 2 μm . We also revealed the pulse width could be tuned by manipulating the driving frequency and repetition rate. Finally, we experimentally observed the phenomenon of RHML at 2 μm and obtained 14 GHz and 21 GHz repetition rate pulses under a 7 GHz driving RF signal. The super-mode suppression ratio of the 21 GHz pulses is 40 dB. Our experimental results enrich our understanding of actively mode-locked fiber operating in the long wavelength, large anomalous dispersion range, and operation based on phase modulators. Such a source can be synchronized to a master clock at a high repetition rate, which shows great potential in high speed 2 μm data-communication and processing.

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