METROLOGY AND MEASUREMENT SYSTEMS
Index 330930, ISSN 0860-8229
www.metrology.pg.gda.pl

PICOSECOND MODE-LOCKED TM-DOPED FIBRE LASER AND AMPLIFIER SYSTEM PROVIDING OVER 20 W OF AVERAGE OUTPUT POWER AT 1994 NM

Paweł Grześ, Maria Michalska, Jacek Świderski

Military University of Technology, Institute of Optoelectronics, Urbanowicza 2, 00-908 Warsaw, Poland
(*pawel.grzes@wat.edu.pl*, *maria.michalska@wat.edu.pl*, ✉ *jacek.swiderski@wat.edu.pl*, +48 261 839 842)

Abstract

A mode-locked Tm^{3+}-doped fibre laser and amplifier operating at a central wavelength of 1994.3 nm is demonstrated. A thulium oscillator is passively mode-locked by a semiconductor saturable absorber mirror to generate an average power of 17 mW at a fundamental repetition rate of 81 MHz in a short linear cavity. This 2-μm laser train is amplified to an average power to 20.26 W by two double-clad thulium-doped all-fibre amplifiers. The pulse energy, duration and peak power is 250 nJ, 23 ps and 9.57 kW, respectively. This represents one of the highest values of average power at $\sim$ 2-μm-wavelength for picosecond thulium-doped fibre lasers and amplifiers. The performance of the laser system is described in details.

Keywords: pulsed fibre lasers and amplifiers, mid-infrared, mode-locked lasers, thulium-doped fibres.

1. Introduction

Thulium-doped fibre lasers and amplifiers operating both in *continuous wave* (CW) [1, 2] and pulse [3] regimes have advanced rapidly in recent years. Due to a very broad emission spectrum spanning from $\sim$ 1.7 to 2.1 μm, high efficiency, high output power, eye-safe wavelength range, diffraction-limited output beam as well as the possibility of all-fibre architecture they have been considered as an important tool for many applications, in medicine [4], spectroscopy [5], LIDAR systems [6], direct energy systems [7], supercontinuum generation [8], and nonlinear frequency conversion [9]. Thulium-doped fibres and Tm-doped fibre laser systems are also a subject of current basic research programs [*e.g.* 10–12].

For some of the applications a train of picosecond pulses of short duration ($<$ 100 ps) with high average output power is often needed. Picosecond pulses at $\sim$ 2-μm-wavelength can be achieved in Tm-doped mode-locked fibre lasers using either active [13, 14] or passive [15–21] methods. The passive mode-locking techniques employ saturable absorbers, such as *semiconductor saturable absorber mirror* (SESAM) [16], *nonlinear amplifying loop mirror* (NALM) [17] or *nonlinear optical loop mirror* (NOLM) [18], carbon nanotubes [19], graphenes [20] and *nonlinear polarization rotation* (NPR) technique [21]. All the techniques have a number of advantages and drawbacks. However, at present the SESAM-based mode-locking technology seems to be the most mature and thus the dominant scheme. SESAMs provide saturable absorption with various characteristics (modulation depth, relaxation time, absorbance) and, what is very important from

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Article history: received on Jun. 25, 2018; accepted on Jul. 28, 2018; available online on Dec. 31, 2018, DOI: 10.24425/mms.2018.124879.

a practical viewpoint, they offer repeatability of the parameters. Furthermore, by using high-precision molecular beam epitaxial growth SESAMs the material composition can be tailored to cover wavelengths emitted by fibre lasers, within the wavelength range of 1–3 μm [22].

Most of the mode-locked fibre lasers provide pulses with a very short duration, usually below 1 ps, and a very low output average power [*e.g.* 19]. The power can be easily boosted in a cascade of amplifiers. However, this approach cannot be easily applied to very short, on a femtosecond scale, and high-peak power pulses since it can lead to pulse distortion or even destruction of the gain medium or some other optical element inside the cavity. Therefore, optical femtosecond pulses before passing through an amplifying medium are first chirped and temporarily stretched and then, after amplification, they are compressed. This technique is commonly known as *Chirped Pulse Amplification* (CPA). This approach, however, makes the whole system more complicated and in most cases it is difficult to be accomplished in the all-fibre format, preferred for many applications.

A spectral bandwidth of mode-locked thulium fibre lasers is usually broad, from several to even hundreds of nm, which facilitates generation of very short femtosecond optical pulses and most of attention has been focused on these lasers. Less concern has been paid to mode-locked thulium fibre laser systems with a narrow bandwidth, especially the ones providing an average output power of tens of watts [*e.g.* 23–25].

In this paper, we present a mode-locked Tm-doped fibre laser and amplifier delivering 23 ps pulses at a fundamental repetition rate of 81 MHz. The pulse energy and peak-power after the amplification were 250 nJ and 9.57 kW, respectively. The maximum average output power was measured to be 20.26 W and currently it is limited by the available pump power.

2. Laser setup

The experimental arrangement of the mode-locked fibre laser and amplifier is shown in Fig. 1. This is a typical *master oscillator – power amplifier* (MOPA) configuration, applied in high power fibre-based laser systems.

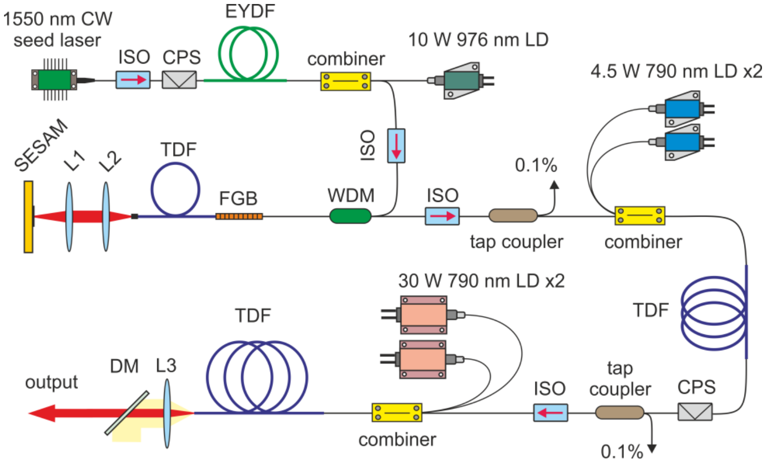

Fig. 1. The experimental setup. EYDF – erbium:ytterbium-doped fibre; TDF – Tm-doped fibre; WDM – 1550/2000 nm wavelength division multiplexer; ISO – optical isolator; CPS – cladding power stripper; DM – dichroic mirror; L1–L3 – lenses; FBG – fibre Bragg grating; LD – laser diode.

The master oscillator has a linear cavity with an overall optical path length of 1.85 m corresponding to a fundamental repetition rate of 81 MHz. A 25-cm-long step-index double-clad polarization-maintaining *Tm-doped fibre* (TDF) with a clad absorption of 4.7 dB/m at 793-nm-wavelength is used as the active medium. A *fibre Bragg grating* (FBG) and a SESAM make up the laser resonator. The gain fibre has a core diameter of 10 μm and a *numerical aperture* (NA) of 0.15. One end of the active fibre is spliced to the FBG with 90% reflectivity at a central wavelength of 1994.5 nm and a *full-width at half-maximum* (FWHM) of 1.4 nm, which is used as the wavelength selecting component and for narrowing pulse spectrum in order to achieve a pulse width of tens of picoseconds. The other TDF end is cleaved at an angle of 8° to avoid parasitic lasing. The SESAM, used in the experiment to maintain mode-locking operation of the laser, has a modulation depth of 20%, a non-saturable loss of 36%, a relaxation time of 10 ps, and a saturation fluence of 35 μJ/cm^2. It is coupled with the angle-cleaved TDF end through two AR-coated aspheric lenses with the same effective focal length of 5.95 mm. The active fibre is backward in-core pumped by a home-made 1550-nm pump unit via a 1550/2000 nm high power fused *wavelength division multiplexer* (WDM) coupler, providing over 90% of pump coupling efficiency. No attempt was made to balance the intra-cavity dispersion.

The 1550 nm pump source consists of a CW semiconductor seed laser and a single-stage *erbium/ytterbium amplifier* (EYDFA) made with the use of a 2.4-m-long Er:Yb-codoped double-clad fibre characterized by 6.5 μm/0.19 NA core and 125 μm/0.45 NA octagonal clad pumped in the counter-propagating scheme (via a multimode pump power combiner) by a fibre-coupled laser diode delivering up to 10 W of continuous power at a wavelength of 976 nm. The clad absorption of the fibre is 0.75 dB/m at 915-nm wavelength, as specified by the manufacturer.

The output fibre end of the 1550/2000 nm WDM, after optical isolation, is spliced to the Tm-doped fibre preamplifier. The 3-m-long active fibre has the same parameters as the one used in the oscillator. The multimode pump combiner with a signal feedthrough is employed to deliver pump light to the TDF from two 790-nm 4.5-W laser diodes with 105/125 μm fibre pigtails (0.22 NA). Following the TDF, a *cladding pump stripper* (CPS) is used to strip the unabsorbed pump light and protect the *optical isolator* (ISO).

The output of the preamplifier, after stripping the unabsorbed pump power and optical isolation, is fusion-spliced to the final Tm-doped fibre power amplifier, built with the use of the large mode area double-clad TDF with a core/clad diameter of 25/250 μm, NAs of 0.08/0.46 and a clad absorption specified as 9.5 dB/m at 793 nm. It is pumped by two fibre-pigtailed multimode 790-nm 30-W laser diodes, light of which is delivered by the $(2{+}1) \times 1$ pump combiner. The active fibre is wrapped on an aluminium drum with a diameter of less than 15 cm to ensure cooling and good beam quality. Its output end is angle-cleaved to avoid unwanted reflections. At the output, a dichroic mirror (HR@0.79 μm, HT@2 μm, 45° coated) is used to filter the unabsorbed 790-nm pump light.

3. Results and discussion

A detailed description of the performance of individual sub-systems is presented in the following subsections. The power was measured with a thermal power meter (Ophir, LaserStar), the spectroscopic measurements were done by an optical spectrum analyzer (Yokogawa, AQ6375). Pulse waveforms were recorded by a 12.5-GHz InGaAs photodetector (Electro-Optics Technology, ET-5000) together with a 6-GHz bandwidth, 25-GSa/s oscilloscope (Tektronix, DSA 70604) as well as an autocorrelator (Femtochrome Research Inc., FR-103WS). The laser beam quality was monitored by a pyroelectric profiler (Ophir, NanoModeScan).

3.1. 1550 nm pump source

The 1550 nm laser system, used for resonant pumping of the Tm-doped fibre oscillator, employed a CW distributed feedback laser delivering up to 45 mW at 1550.12 nm with a < 50 nm FWHM spectrum width. Then, after optical isolation, the signal was amplified in the Er:Yb-codoped fibre amplifier pumped at a 976-nm wavelength. This simple configuration provided a stable pump beam with maximum power of 2.25 W (Fig. 2).

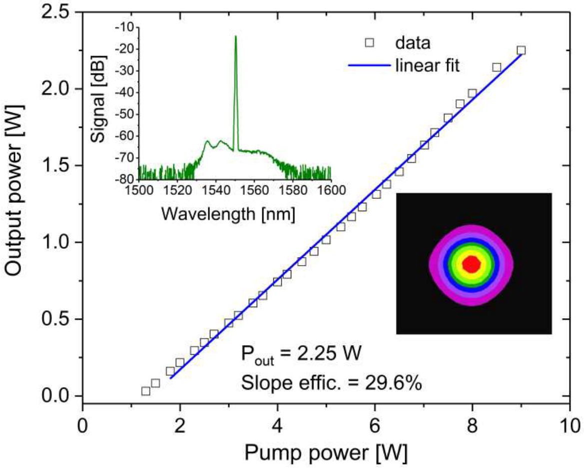

Fig. 2. Output power at 1550 nm versus pump power. Top and bottom insets present the output spectrum and the far-field beam profile, respectively.

The booster amplifier was pumped with a continuous power of up to 9 W and the pump wavelength was tuned so as to match the maximum of active medium absorption peak. The output power increased nearly linearly over the whole pump power range applied with a slope efficiency of 29.6% determined in reference to the launched pump power. The slope efficiency and thus the output power could be further increased by more accurate system optimization, mainly by applying a more powerful seed laser providing better amplifier saturation. The spectrum of output beam is clear without significant spectral distortions. The visible *amplified spontaneous emission* (ASE) signal is negligible and the *noise-to-signal ratio* (SNR) is over 50 dB (upper inset). The intensity profile of the output beam was measured with the use of a fully automated M^2 system using a beam propagation analyser with a pyroelectric profiler, making the measurements consistent with the ISO 11146 requirements. An example of a far-field beam profile is shown in the inset in Fig. 2. The beam was only diffraction-limited with M^2 factor below 1.1.

3.2. Thulium-doped fibre oscillator

The Tm-doped fibre oscillator, after a proper adjustment of the SESAM, provided stable CW mode-locked pulses with a repetition rate of 81 MHz, corresponding to the optical cavity length (Fig. 3).

The maximum average output power for stable mode-locking was measured to be 17 mW corresponding to a pump power of ~ 430 mW. When the higher pump power was applied the

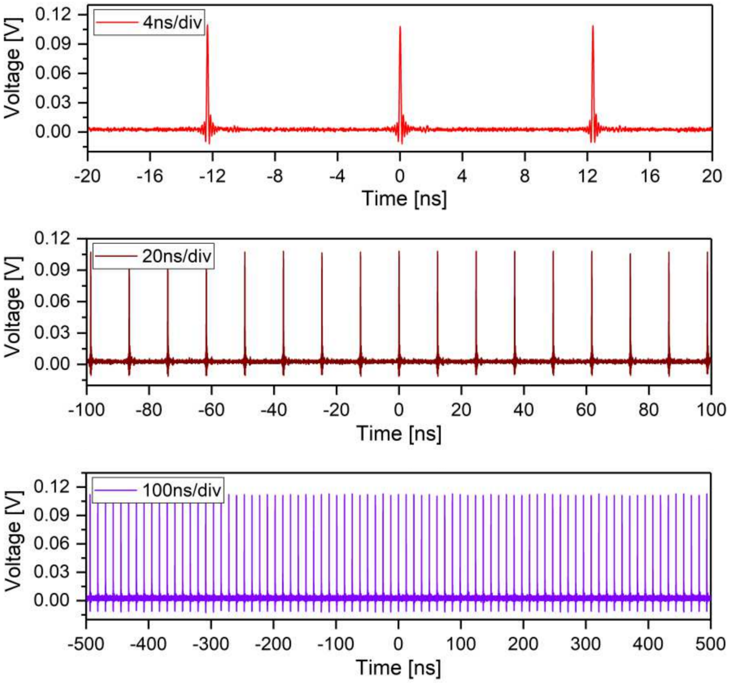

Fig. 3. A train of 2-μm pulses recorded for three different time scales.

laser started to operate unstably. The laser operated at a central wavelength of 1994.3 nm with a 3 dB width of 0.27 nm (Fig. 4). The SNR was measured to be 44 dB (Fig. 5). The duration of output pulses could not be measured by our auto-correlator because of their low peak power. Therefore, the pulse width was measured after the final amplifier.

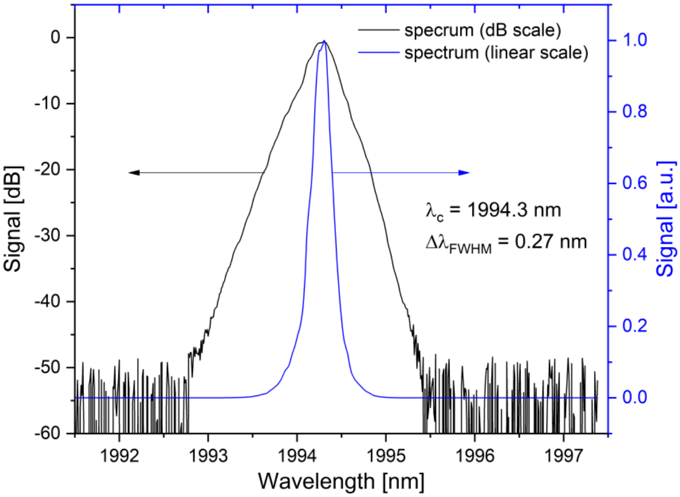

Fig. 4. A spectrum of 2-μm pulses presented in dB and on a linear scale.

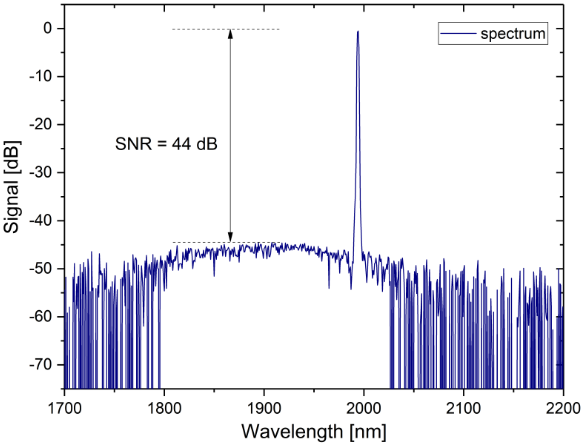

Fig. 5. A spectrum of 2-μm pulses recorded over a 500-nm bandwidth scale.

3.3. Thulium-doped fibre preamplifier

In the next step, the pulses from the output of the seed oscillator were launched into the Tm-doped fibre preamplifier in order to provide enough power for the final power amplifier. Fig. 6 illustrates the average output power of the amplified pulse train as a function of the absorbed pump power, whereas oscilloscope traces of mode-locked pulses before and after amplification are presented in Fig. 7.

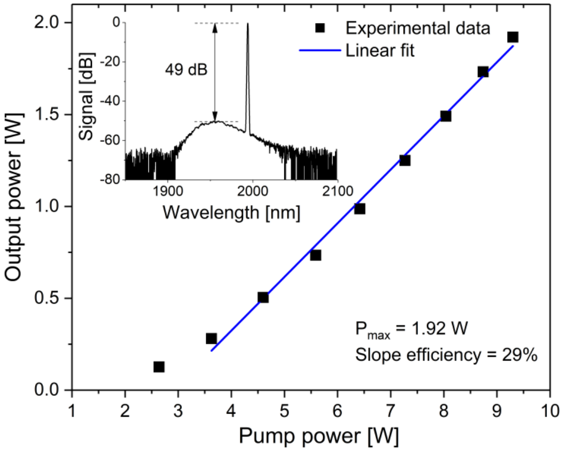

Fig. 6. The output power versus the pump power launched into the Tm-doped fibre preamplifier. Inset: the optical spectrum measured over a 250-nm bandwidth scale, at an output power of 1.9 W.

The average output power increased with the pump power and reached the maximum value of 1.92 W at an absorbed 790-nm pump power of 9.3 W, with a slope efficiency of 29%. The amplifier provided more than 20 dB of gain and delivered single mode-locked pulses without multiple pulse operation (Fig. 7). Except for a small ASE signal, no obviously nonlinear effects

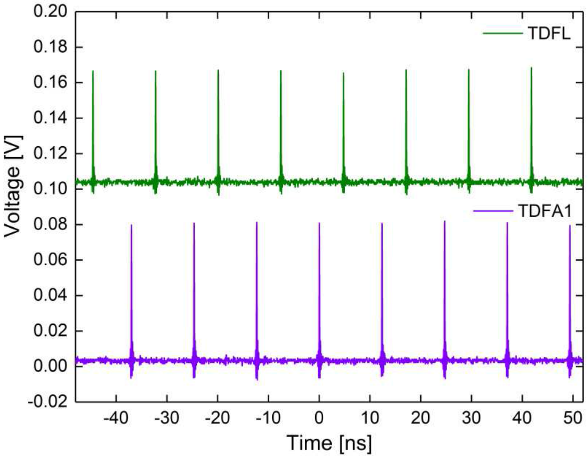

Fig. 7. Stable passively mode-locked pulse trains before (upper) and after (bottom) amplification.

were observed in the optical spectrum, as shown in the inset in Fig. 6. The SNR was measured to be 49 dB. The central wavelength and the spectral bandwidth of the signal measured at the amplifier output were almost the same as in the case of the oscillator.

3.4. Thulium-doped fibre power amplifier

The final power amplifier was assembled in a similar way as the preamplifier. A 3.4-m-long large mode area TDF with a core 25 μm was employed mainly to avoid nonlinear effects occurring during amplification of short optical pulses. The average power of an incident pulse train, launched into the gain fibre, was 0.9 W. The booster amplifier delivered an average output power of 20.26 W for 51 W of absorbed pump power, which corresponds to a slope efficiency of 43% (Fig. 8). As can be seen, the output power increased almost linearly with the rise of

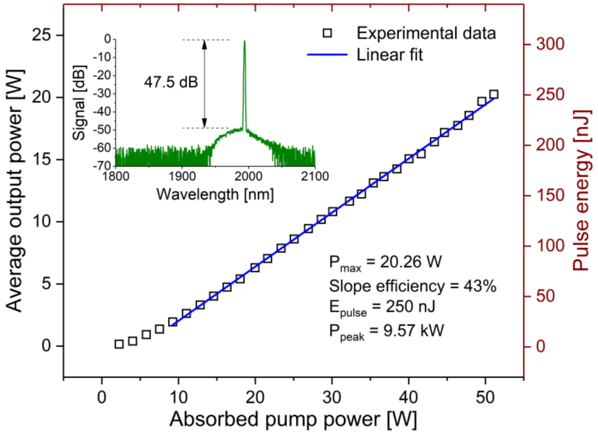

Fig. 8. An average output power and pulse energy of the Tm-doped booster amplifier as a function of absorbed 790-nm pump power. Inset: a spectrum of amplified pulses recorded over a 300-nm bandwidth scale.

pump power with no roll-off of the curve thus showing that the power can be further increased by applying more pump power. The maximum pulse energy was 250 nJ, calculated by dividing the output power by the pulse repetition frequency.

The output spectrum was also clear without any artifacts coming from nonlinear effects (inset in Fig. 8). The ASE signal in the amplifier is about 47.5 dB down compared with the amplified signal, showing that the MOPA operates with very low-intensity noise.

The autocorrelation trace of the amplified pulses measured at an average output power of 20 W is depicted in Fig. 9.

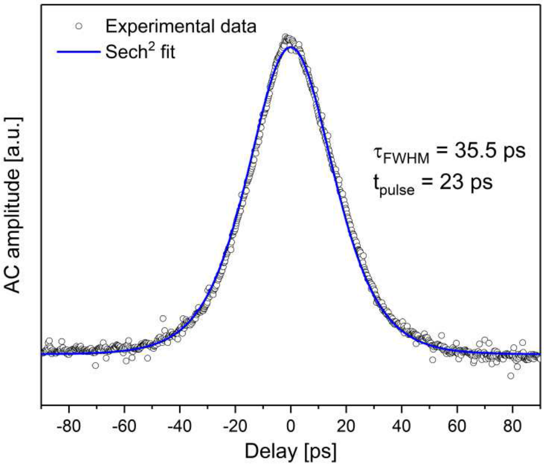

Fig. 9. An autocorrelation trace of the amplified pulses and its sech^2 fit (solid curve).

The FWHM of the autocorrelation trace was 35.3 ps. If a squared hyperbolic secant pulse profile is assumed, the pulse width is 23 ps. Consequently, the time-bandwidth product, when combined with the 0.27 nm spectral bandwidth, was calculated to be 0.47, which is slightly higher than the theoretical transform limit. With a better dispersion management in the laser cavity, shorter mode-locked pulses are expected. The maximum peak-power of the amplified pulses was 9.57 kW. The average output power can be further scaled up by increasing the pump power of the booster amplifier. The output beam was also characterized by very good quality with M^2 factor below 1.2, which is a typical value for large mode area fibres.

4. Conclusions

In conclusion, we have demonstrated a pulsed fibre-based laser system operating at a wavelength of 1994.3 nm. A SESAM passively mode-locked Tm-doped fibre laser emitting a train of 23-ps pulses at a repetition rate of 81 MHz is used as the master oscillator. The seed pulse train is amplified to 20.26 W by using a two-stage Tm-doped fibre amplifier, yielding pulse energies of 250 nJ and a pulse peak power of 9.57 kW. Further increases in the average power and shortening the pulse width are expected with the application of a higher pump power of the booster amplifier and suitable compensation of the thulium oscillator dispersion, respectively. The laser system can be used for pumping OPO and soft-glass fibres to achieve laser radiation in the mid-IR wavelength range.

Acknowledgements

This research leading to these results was mainly supported by the National Science Centre, Poland (grant No. UMO-2014/13/B/ST7/00442).

Pawel Grześ would like to acknowledge the financial support (scholarship) from the Polish National Science Centre. Special acknowledgments are given to Marcin Mamajek and Jan Karczewski from the Institute of Optoelectronics MUT for discussions and the technical support.

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