IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 10, Number 5, September 2018

Baldemar Ibarra-Escamilla
Manuel Durán-Sánchez
Berenice Posada-Ramírez
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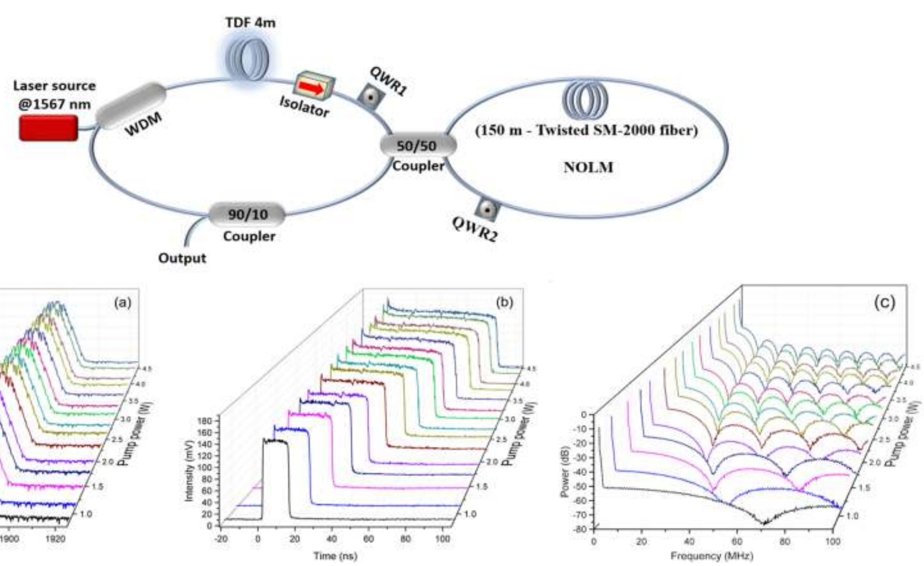
Evgeny A. Kuzin



DOI: 10.1109/JPHOT.2018.2870572

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Dissipative Soliton Resonance in a Thulium-Doped All-Fiber Laser Operating at Large Anomalous Dispersion Regime

Baldemar Ibarra-Escamilla,[1] Manuel Durán-Sánchez ,[2] Berenice Posada-Ramírez ,[1] Héctor Santiago-Hernández,[3] Ricardo Iván Álvarez-Tamayo ,[4] David Sánchez de la Llave,[1] Miguel Bello-Jiménez,[5] and Evgeny A. Kuzin[1]

[1]Instituto Nacional de Astrofísica, Óptica y Electrónica, Puebla 72824, Mexico
[2]CONACyT—Instituto Nacional de Astrofísica, Óptica y Electrónica, Puebla 72824, Mexico
[3]Departamento de Electrónica, Universidad de Guadalajara, Guadalajara 44840, Mexico
[4]CONACyT—Universidad Autónoma de Nuevo León, Nuevo León 66451, Mexico
[5]Instituto de Investigación en Comunicación Óptica, Universidad Autónoma de San Luis Potosí, San Luis Potosí 78210, Mexico

DOI:10.1109/JPHOT.2018.2870572

Manuscript received July 6, 2018; revised September 5, 2018; accepted September 12, 2018. Date of publication September 17, 2018; date of current version October 4, 2018. This work was supported by CONACyt proyect 256401. Corresponding author: M. Durán-Sánchez (e-mail: manueld@inaoep.mx).

Abstract: We experimentally demonstrate dissipative soliton resonance effect in a 173-m long passively mode-locked figure-eight thulium doped fiber laser with a net anomalous dispersion. The duration of the wave-breaking-free pulse broadens with the increase of a pump power. At maximum pump power of 4.5 W, square pulses were generated with duration of 85.18 ns, average output power of 245 mW, pulse energy of 206 nJ, and repetition rate of 1.19 MHz.

Index Terms: Fiber laser, mode-locked lasers, pulse propagation, temporal solitons.

1. Introduction

Mode-locked thulium-doped fiber lasers (TDFLs) in the 2-μm wavelength band have been the subject of increasing interest for a wide range of applications in different research areas, such as microscopy [1], fiber amplifiers [2], nonlinear frequency conversion for mid-IR and THz generation [3], welding of polymeric materials [4], gas detection and analysis [5], among others. Passively mode-locked fiber lasers are considered very useful optical sources to generate stable and coherent ultrashort optical pulses. In TDFLs the generation of conventional solitons [6], [7], dissipative solitons [8], [9], and also the effect of the dissipative soliton resonance (DSR) [1], [2], [10]–[13] were demonstrated. Besides this, some quasi-stable dynamics such as the noise-like pulse (NLP) regime have been also reported [14], [15]. Several mode-locking mechanisms which include semiconductor saturable absorber mirror (SESAM) [8], [16], carbon nanotubes (CNTs) [17], graphene [7], [18], nonlinear polarization evolution (NPE) [14], [19], [20], nonlinear optical loop mirror (NOLM) [2], [14], and even combinations of them have been reported to perform a stable train of mode-locked optical pulses [21]. Saturable absorbers (SA) based on a nonlinear optical effect have the response time of around 5 fs. With combination of a nonlinear amplified fiber loop mirror (NALM) with a CNT SA,

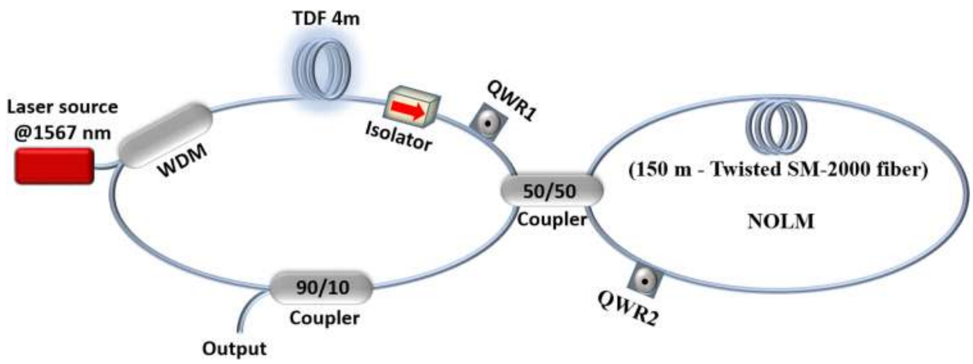

Fig. 1. Schematic of the experimental setup. WDM: wavelength division multiplexer. TDF: Thulium doped fiber. QWR: quarter-wave retarder. NOLM: nonlinear optical loop mirror.

mode-locked pulses with short duration of 230 fs were reported [22]. Moreover, SESAM, CNTs and graphene exhibit some drawbacks including complex design for improving of damage threshold. On the other hand, most of the reported investigations on DSR effect have been done based on two different mechanisms: the use of NPE technique and a NOLM-based laser configuration.

In the framework of rectangular pulse generation, the DSR regime at the 2 μm wavelength region is relatively new. Theoretical studies of DSR based on the numerical solution of the complex cubic-quantic Ginsburg-Landau equation have been reported [23], [24]. DSR pulsed regime has unique properties such as long pulse duration, giant chirp and large pulse energy. In order to obtain high-power stable nanosecond-scale laser pulses, active Q-switching [25] and gain-switching [26] are commonly used techniques, however, these techniques require complex electronics for precise controlling of the output pulse characteristics, and exhibit lack of ability to operate in various pulse-shaping regimes. Conversely, mode-locked fiber lasers provide various pulse-shaping regimes based on nonlinear and dispersion mechanisms with less controlling components. In this regard, DSR promises to be an effective technique to generate rectangular-shape pulses in the nanosecond pulse duration range. DSR can be achieved in both anomalous and normal dispersion regimes [27], [28]. Most of the experimental results on DSR generation have been demonstrated for ytterbium [29]–[33], erbium [34]–[38], and erbium-ytterbium double clad fiber lasers [39]–[46]. However, a limited number of researches have been performed on DSR pulse operation in the 2 μm wavelength region. Y. Xu *et al.* reported an all-fiber figure-eight mode-locked thulium doped fiber laser with net-normal dispersion with pulse energy of 19.51 nJ and pulse width of 6.19 ns [10]. S. Tan *et al.* reported DSR in a TDFL with anomalous dispersion and pulse width of 438 ps for applications in microscopy [1]. J. Zhao *et al.* reported DSR in a thulium-doped double-clad fiber (TDCF) laser and demonstrated up to 100 W of average power, and pulse duration of 72.19 ns at repetition rate of 1.065 MHz [2]. Most recently, T. Du *et al.* reported a high power, large-energy DSR in a 2 μm TDCF laser, with central wavelength at 2005.9 nm, pulse duration of 13.7 ns, and a maximum average power of 1.4 W at a repetition rate of 3.37 MHz [11]. W. Ma *et al.* in ref. [12] and T. Wang *et al.* in ref. [13] demonstrated differences of spectral and temporal profiles between square-shape noise like pulses (NPL) and pulses generated at DSR.

In this paper, we demonstrate DSR operation in a figure-eight TDFL based on a polarization asymmetrical NOLM. Experimental results show stable train of DSR pulses with a repetition rate of 1.19 MHz. The pulse width can be tuned from 14.24 ns to 85.18 ns by increasing the pump power from 0.88 W to 4.5 W. For the maximum pump power of 4.5 W, the average output power is 245 mW with pulse energy of ~206 nJ.

2. Experimental Details

The experimental setup of the laser is shown in Fig. 1. The mode-locking mechanism is based on the use of a nonlinear optical loop mirror (NOLM) as SA. The NOLM is formed by a 50/50

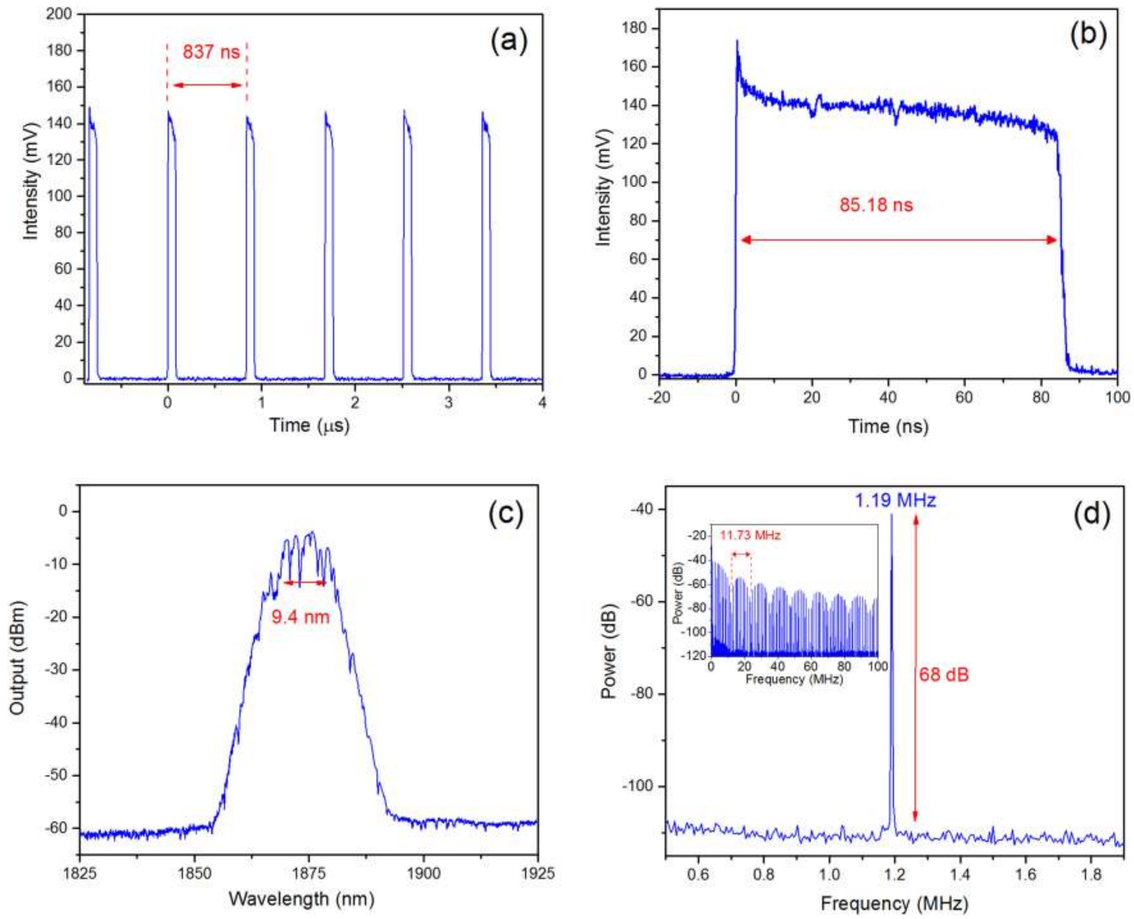

Fig. 2. Square-wave pulse emission of the laser with the maximum pump power of 4.5 W. (a) Pulse train. (b) Temporal profile of single DSR pulse. (c) Optical spectrum of the DSR pulse. (d) RF spectrum of the output pulse train. The inset shows the frequency modulation.

coupler whose output ports are connected by a 150-m long SM-2000 fiber twisted at a rate of 7 turns per meter (twist eliminates the fiber residual birefringence, and light ellipticity is conserved during propagation). Although the NOLM is symmetric in power, polarization imbalance is induced by a quarter-wave retarder (QWR2) inserted in the loop. The active medium is provided by a 4-m long thulium-doped fiber (TDF) (CorActive SCF-TM-8/125) with core diameter of 8 μm, numerical aperture (NA) of 0.17, and 13 dB/m absorption at 1567 nm. The laser cavity is completed by an isolator (ISO) to ensure unidirectional laser operation, and a 90/10 coupler, which provides the laser output. A quarter-wave retarder (QWR1) is used to establish circular polarization at the NOLM input. The TDF is pumped by an Er/Yb fiber laser through a 1550/2000 WDM. The maximal pump power was 4.5 W at wavelength of 1567 nm. The 10% output port of the 90/10 optical fiber coupler was used to provide the laser output, the 90% port was connected to the WDM. The laser output power is measured by a thermal optical power meter (Thorlabs PM310D). The output pulses are detected by a high-speed photodiode (12.5 GHz bandwidth and 28 ps rise/fall time) and monitored by a real time 2.5 GHz bandwidth oscilloscope. The spectrum was measured by an optical spectrum analyzer (OSA, Yokogawa AQ6375) with scanning range from 1200 to 2400 nm and maximal resolution of 0.05 nm. We have also measured the radio-frequency (RF) spectrum of the output pulses by using the high-speed photodiode together with a spectrum analyzer with 10 Hz $-$ 3 MHz resolution bandwidth and frequency span range of 100 Hz $-$ 20 GHz (Agilent, N9344C Handheld spectrum analyzer). The measured total cavity length is of 173 m, including the TDF, the SM-2000 fiber, and

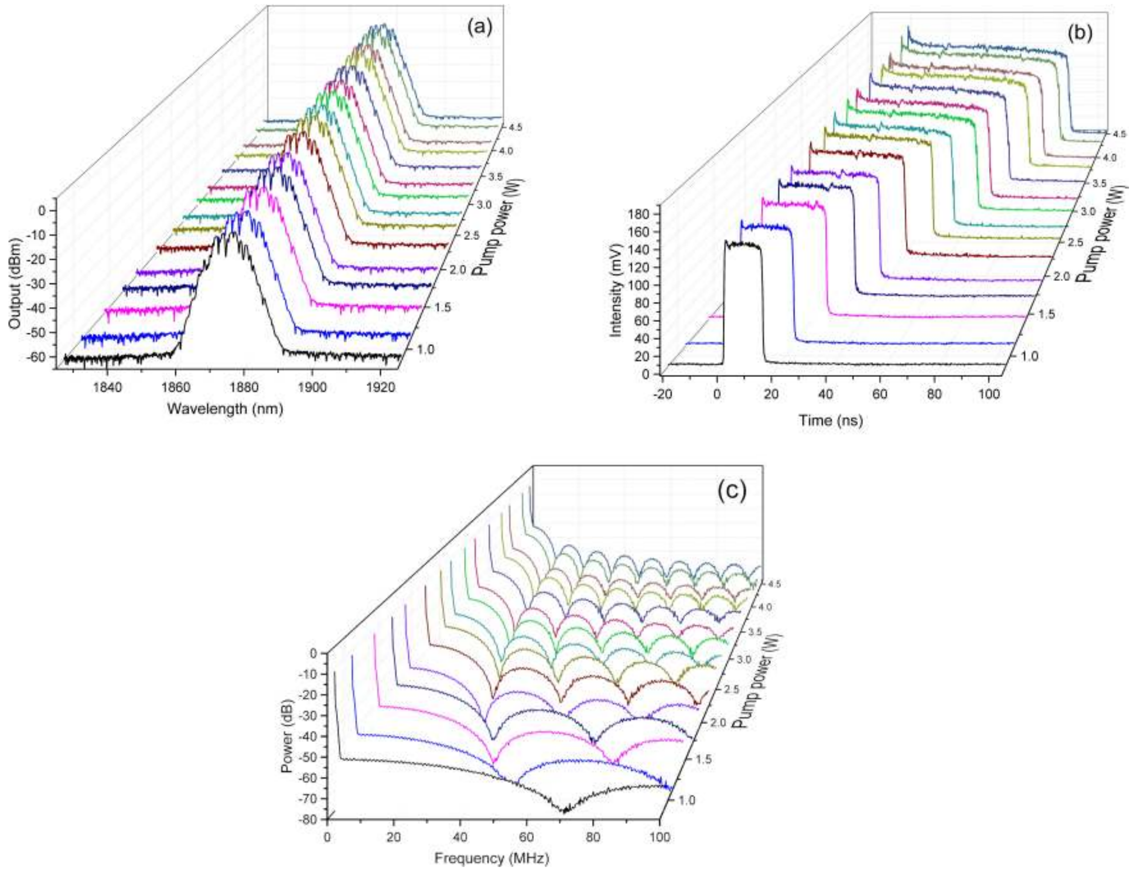

Fig. 3. DSR laser characteristics on pump power variations. (a) The optical spectrum vs pump power. (b) Evolution of rectangular pulses with pump power. (c) RF spectrum evolution with pump power.

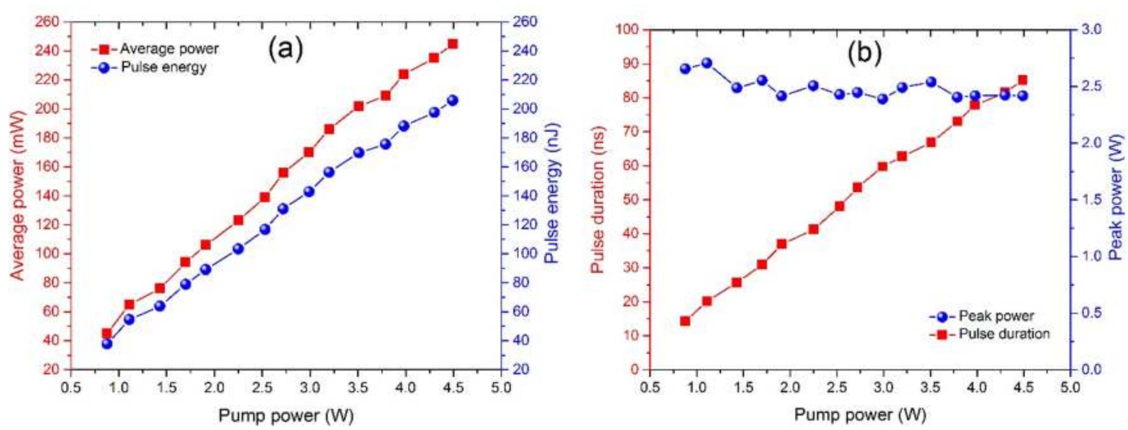

Fig. 4. Pulse parameters as a function of pump power. (a) Average output power and pulse energy. (b) Pulse duration and peak power.

19-m of SMF-28e fiber which correspond to the fiber pigtails of the WDM, the ISO, and the optical couplers. The dispersion values at 1.9 μm of the TDF, the SM2000 fiber, and the SMF-28e fiber, were estimated of -84, -73, and -80 ps^2/km, respectively [20]. These values yield the net cavity dispersion of -12.81 ps^2, which means that the laser is operating in large anomalous dispersion regime.

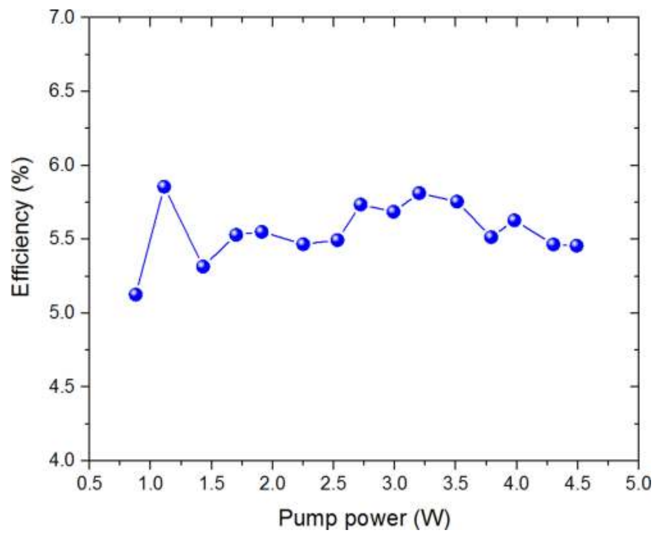

Fig. 5. DSR laser power efficiency as a function of the pump power.

3. Results

Self-started mode-locking of the figure-eight fiber laser is achieved at the pump power of 0.88 W. With proper rotation of the QWR1 and QWR2, a stable mode locking operation was observed. The typical characteristics of mode-locked pulses are shown in Fig. 2 at the maximum pump power of 4.5 W. As shown in Fig. 2(a), fundamental mode-locking is evidenced by the appearance of a stable train of pulses with a period of 837 ns, meaning that a single pulse circulates in the 173 m long cavity. The pulse is also measured in the time domain by using a 50-GHz sampling oscilloscope, as shown in Fig 2(b); the measurement shows that the pulse has a square waveform and duration of 85.18 ns. The respective optical spectrum is illustrated in Fig. 2(c). A wide and smooth spectrum is obtained with a maximum near to 1873.5 nm, although the trace presents a water absorption band in the spectrum. The 3-dBm bandwidth is 9.4 nm. The measured RF spectrum shows a signal to noise ratio of 68 dB, using a 1.4 MHz span and 100 Hz bandwidth. The inset in Fig. 2(d) exhibits a characteristic modulation with a period of 11.73 MHz, corresponding to the duration of the generated pulses for 4.5 W of pump power.

The main characteristics of pulses at different pump power in the range between 0.85 W and 4.5 W are shown in Fig. 3. Fig. 3(a) shows the optical spectra centered at 1873.5 nm with a SNR value of ∼55 dB. The spectra have the same profile for the pump power in the range between 0.88 W and 4.5 W. Because that the DSR light pulse have a low linear chirp across the pulse, except at the edges, where the chirp changes exponentially [32]. As it can be expected from DSR laser operation, as the pump power is increased, the duration of the squared pulses increases [see Fig. 3(b)], whereas the optical spectrum of the laser output remains constant [see Fig. 3(a)]. In the pump power range from 0.88 to 4.5 W the squared pulses width increases from 14.24 to 85.18 ns. In order to confirm stable DSR laser operation, the RF spectrum was measured with a 100 MHz span and 1 kHz resolution. As it can be observed in Fig. 3(c), the frequency of the first power minimum decreases from 70.22 MHz to 11.73 MHz as the pump power is increased from 0.88 to 4.5 W. These frequency displacements correspond to the pulse duration variations from ∼14.24 ns to ∼85.8 ns. Then, the modulation pattern is defined by the duration of generated pulses, which corresponds to the reciprocal value of the pulse duration.

Fig. 4 shows the average power, pulse duration, pulse energy, and peak power as a function of the pump power variations. Fig. 4(a) shows an increasing linear dependence of the average power and the pulse energy with the pump power. At the maximum pump power of 4.5 W, the average output power is of 245 mW and the pulse energy is of ∼206 nJ. From Fig. 4(b) can be observed pulse duration increase from 14.24 to 85.18 ns as the pump power is increased from 0.88 to 4.5 W.

Then, considering a pulse repetition rate of 1.19 MHz, calculated peak power of ~2.4 W remains constant for all the pump powers.

Fig. 5 shows the conversion efficiency from pump power to output average power as a function of the pump power in the range from 0.8 W to 4.5 W, in which the pulse duration increases from 14.24 ns to 85.18 ns. The conversion efficiency is of ~5.5% and does not depend on the pump power. The relatively low optical power efficiency could be attributed to excessive fiber length that significantly increases the cavity losses, and also to the 10% output power extracted with the 90/10 coupler.

4. Conclusion

In summary, we demonstrated DSR effects in a passively mode-locked figure-eight thulium doped fiber laser. By the proper setting of the QWR1 and QWR2 self-started mode-locking is achieved at the pump power of 0.88 W. With the increase of the pump power from 0.88 W to 4.5 W, the DSR square pulses width enlarges from 14.24 ns to 85.18 ns, the average power increases from 45 mW to 245 mW, and the pulse energy increases from 37.8 from ~206 nJ at the 1.19 MHz repetition rate.

Acknowledgment

M. Durán-Sánchez and R. I. Álvarez-Tamayo would like to thank to Cátedras Consejo Nacional de Ciencia y Tecnología program.

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