Square pulse emission with ultra-low repetition rate utilising non-linear polarisation rotation technique

Sin Jin Tan[1,2], *Zian Cheak Tiu*[1,2], *Sulaiman Wadi Harun*[1,2], *Harith Ahmad*[2]

[1]*Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[2]*Photonics Research Center, University of Malaya, 50603 Kuala Lumpur, Malaysia*
E-mail: swharun@um.edu.my

Published in *The Journal of Engineering*; Received on 27th July 2014; Accepted on 20th August 2014

Abstract: The generation of nanosecond square pulse and microsecond harmonic pulse in a passively mode-locked fibre ring laser is demonstrated by inserting a 20 km long single mode fibre in the cavity. The laser operates in anomalous region based on the non-linear polarisation rotation process. The square pulse generation is because of the dissipative soliton resonance effect, which clamps the peak intensity of the laser and broadens the pulse width. The pulse width can be tuned from 28.2 to 167.7 ns. It was found that the square pulse can deliver higher pulse energy compared with the harmonic pulse. The highest recorded pulse energy is 249.8 nJ under the maximum available pump power of 125 mW without pulse breaking.

1 Introduction

A resonator that is kilometres long offers lower fundamental repetition rate in the kilohertz and hence allows the deliverance of higher pulse energy. However, there is a challenge that needs to be overcome if the oscillator is long. The combined action of both Kerr non-linearity and dispersion generally leads to pulse break up (multi-pulse) after the accumulated non-linear phase has exceeded a certain level. Pulse breaking leads to higher repetition rate and lower pulse energy compared with single pulse operation. Apart from the dissipative soliton (DS) with steep spectral edges, a new approach, namely the DS resonance (DSR) has been suggested to increase the pulse energy from a fibre laser. The formation of DSR is based on certain parameters selection within the frame of complex Ginzburg–Landau equation, where its pulse energy can be increased infinitely. DSR is recognised as a square pulse with flat top and steep edges, and thus its pulse duration is rather broad. It normally operates in the nanosecond region. Since the first demonstration of the square pulse emission by Matsas *et al.* [1], research effort on this topic has been lacking.

Recently, DSR pulse with higher pulse energy has been demonstrated by many researchers [2–6]. The formation of square pulse is theoretically independent of the sign of cavity dispersion and has been proven where square pulse can be formed in the positive [4] and negative [2] dispersion regions. Based on the previously published reports, the lowest attainable repetition rate was 173.05 kHz, which was obtained by inserting 1.16 km of highly non-linear fibre (HNLF) [6]. DSR pulse is also observed to be able to maintain single pulse operation, compared with the conventional DS pulse where DS pulse broke into five pulses at maximum available pump power [7]. The majority of the experiments conducted adopted a long piece of fibre such as single mode fibre (SMF) and HNLF. Therefore it is predicted that the formation of DSR requires large dispersion and high non-linearity.

Recently, some reports showed that mode-locked fibre lasers can deliver pulses with different duration simultaneously. For instance, Mao *et al.* [8] demonstrated a mode-locked fibre laser delivering both conventional and DSs pulses. More recently, Han *et al.* [9] demonstrated simultaneous generation of picosecond and femtosecond solitons using a carbon nanotubes (CNTs) saturable absorber. In this paper, nanosecond DSR square pulse generation with an ultra-low repetition rate of 10.2 kHz is demonstrated by inserting a 20 km long SMF in a simple ring resonator. The proposed laser can deliver nanosecond square pulse and microsecond harmonic pulse by adjusting a polarisation controller (PC). It is worth noting that although the cavity length is significantly long, the fibre laser still operates at its fundamental repetition rate without pulse breaking. By manipulating the polarisation state in the cavity, the proposed laser can also be adjusted to operate in harmonic mode. The performance of this harmonic laser with sech^2 shape is also investigated for comparison purposes. It is found that the pulse energy produced by DSR square pulse is much higher compared with the harmonic pulse.

2 Experimental setup

The experimental setup of the proposed mode-locked fibre laser is schematically shown in Fig. 1. It uses a 4.5 m long erbium-doped fibre (EDF) with an erbium concentration of 2000 ppm, cut-off wavelength of 910 nm, a pump absorption coefficient of 24 dB/m at 980 nm and a dispersion coefficient of −21.64 ps/nm km at $\lambda = 1550$ nm, as the gain medium. The EDF is pumped with a 1480 nm laser diode through a 1480/1550 nm wavelength division multiplexer. A polarisation dependent isolator (PDI) is used to ensure unidirectional propagation of light in the cavity and at the same time to generate linear light polarisation. A PC is employed to adjust the polarisation of light. A 20 km spool of SMF constitutes the long cavity and also serves to increase the non-linearity and dispersion. The dispersion parameter of the SMF is 17 ps/nm km. About 50% of the circulating light is taken out of the cavity via a 3 dB coupler and then fed into another 3 dB coupler. The second coupler splits the light for simultaneous monitoring, one part into an optical spectrum analyser (OSA) and the other into an oscilloscope and radio-frequency spectrum analyser together with a high-speed photodetector. The cavity is operating in a large negative dispersion region because of the long SMF.

3 Results and discussion

The mode-locked laser is generated based on non-linear polarisation rotation (NPR) effect in the ring cavity. The polarising isolator placed beside the PC acts as the mode-locking element in the proposed laser. It plays the double role of an isolator and a polariser, such that light leaving the isolator is linearly polarised. Consider a linearly polarised pulse just after the isolator. The polarisation state evolves non-linearly during the propagation of the pulse inside the EDF and SMF because of self-phase modulation and cross-phase modulation effects in the ring cavity. The state of

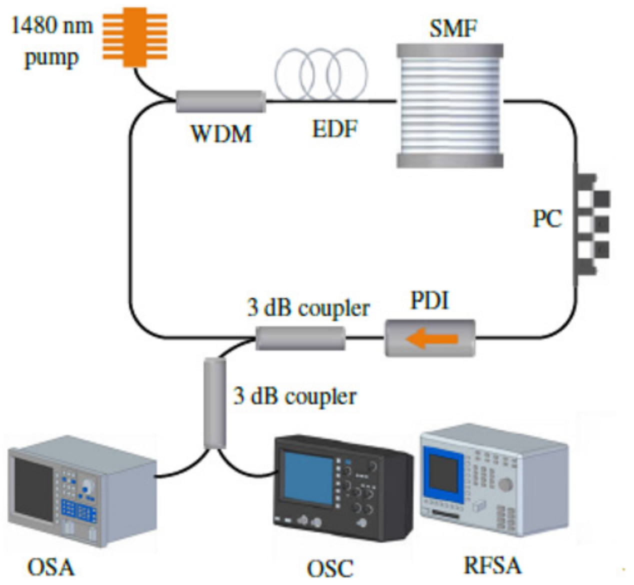

Fig. 1 *Experimental setup of the proposed DSR laser*

polarisation is non-uniform across the pulse because of the intensity dependence of the non-linear phase shift. The PC is adjusted so that it forces the polarisation to be linear in the central part of the pulse. The polarising isolator lets the central intense part of the pulse pass but blocks (absorbs) the low-intensity pulse wings. The net result is that the pulse is slightly shortened after one round trip inside the ring cavity, an effect identical to that produced by a fast saturable absorber (SA). In another words, the PDI, working together with the birefringence fibres, generates an intensity dependent loss mechanism in the cavity that contributes to mode-locked square pulse generation in the cavity.

Apart from NPR technique, SA such as CNTs and graphene can also be used to initiate mode-locking. For instance, Liu *et al.* [10] reported a highly stable mode-locked fibre laser with a multi-wavelength output based on CNTs. In another work, mode-locked fibre laser emitting both dissipative and conventional solitons is also demonstrated by using a more complex nanomaterial based saturable absorber, which was obtained by mixing graphene and CNTs [11]. However, the square pulse phenomenon is not observed in both experiments when CNTs or graphene is used. This could be because of the cavity loss, which is drastically increased when these SAs are inserted into the laser cavity.

In the proposed experiment, by careful adjustment of the PC, stable square pulse starts to form at pump power of 108 mW. Fig. 2 shows the optical spectrum of the typical square pulse emission from the laser at three different pump powers of 108, 112 and

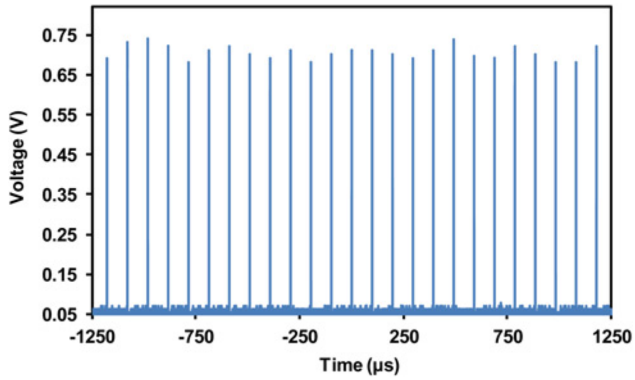

Fig. 3 *Fundamental repetition rate at 10.2 kHz*

125 mW. At the maximum pump power of 125 mW, the laser operates at 1568.7 nm with the peak power of −17.2 dBm and 3 dB bandwidth of about 1 nm. Fig. 3 shows the oscilloscope trace of a square pulse train. The pulse train has an ultra-low repetition rate at 10.2 kHz, as determined by the cavity length. Fig. 4 focuses on a single pulse at two different pump powers. As shown in the figure, the square pulse has the distinct characteristic of steep leading and trailing edges and its pulse width can be tuned by changing the pump power. At 120 mW, the measured pulse width is 120.0 ns, whereas at 125 mW pump power, the pulse width increases to 167.7 ns. At the maximum pump power, the pulse still has a square shape while keeping the peak power almost constant. With the orientations of the wave-plates fixed, it is observed that the peak power of the square pulse is maintained while the pulse width increases with pump power. The ripple structures on the top of the pulse are probably because of insufficient gain to compensate for the loss in the ultra-long cavity. A cleaner square pulse structure is expected at higher pump power.

As shown in Fig. 2, the shape and 3 dB bandwidth of the mode-locked spectra are almost invariable with pump power. It is believed that the square pulse formed here has the characteristic of a square shape which undergoes pulse broadening with constant peak power and also invariable 3 dB optical bandwidth spectra which resembles the DSR theory that is predicted by Chang *et al.* [12, 13]. The theory of DSR indicates that the pulse energy could be boosted up to an infinitely large value, whereas the square pulse duration will broaden with increasing pump power while pulse amplitude converges to a given plateau value when the cavity parameters are chosen near to the resonance curve.

The evolution of pulse width with respect to pump power is presented in Fig. 5. The pulse width can be tuned from approximately 28.2 ns to 167.7 ns without pulse breaking by increasing pump power from 108 to 125 mW. The generation of square pulse in

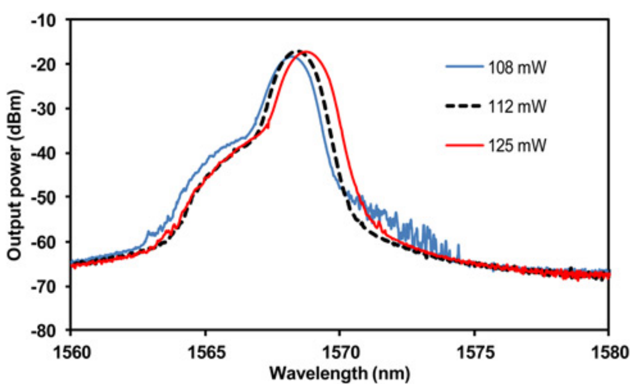

Fig. 2 *Optical output spectra of pulse laser at three different pump powers*

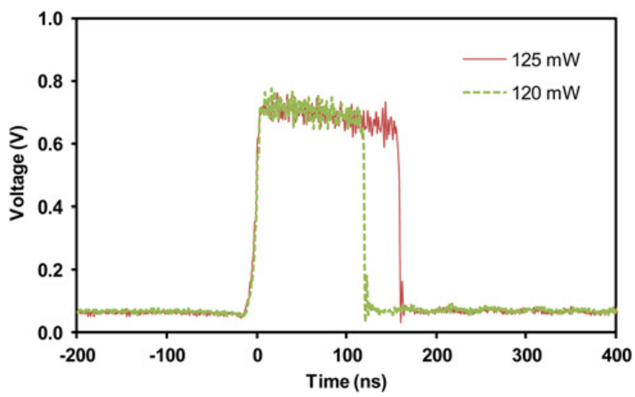

Fig. 4 *Oscilloscope of single square pulse at different pump powers*

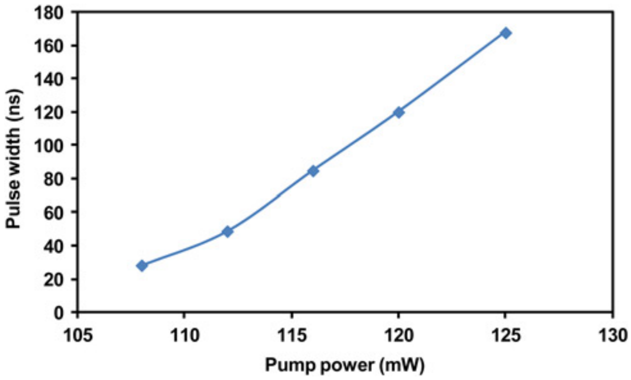

Fig. 5 *Pulse width of the square pulse against pump power*

the long cavity is most probably because of the DSR phenomenon in the long cavity laser. After the generation of square pulse, the peak amplitude is kept almost constant and does not increase with pump power anymore. The excess power circulating in the cavity now accounts for the increase in the pulse width rather than the peak intensity. Owing to the increment of pulse width, the pulse energy could be increased greatly as opposed to other soliton operation regions.

Fig. 6 shows the RF spectrum of the mode-locked fibre laser (at pump power of 125 mW) for both square and harmonic pulses, which reveals the repetition rates of 10.2 and 20.4 kHz, respectively. The signal-to-noise ratio (SNR) is obtained from the intensity ratio of the fundamental peak to the pedestal extinction, estimated to be ∼32 and 40 dB for square and harmonic pulses, respectively, which indicates the stability of the laser. However, the SNR value is lower compared with other mode-locked fibre laser, which usually has an SNR of about 50 dB [14]. This is attributed to the cavity length used, which is significantly longer.

The square pulse can be switched to harmonic pulse operating in microsecond region by careful adjustment of the PC while maintaining all other cavities' parameters. Self-starting harmonic mode-locking can be realised by an appropriate adjustment of polarisation of light and at an adequate pump power. When pump power is raised to ∼100 mW, mode-locked pulse is formed with repetition rate of 10.2 kHz which corresponds to the fundamental frequency. As the pump power is increased to 108 mW, pulse breaking is observed where its repetition rate doubles to 20.4 kHz, representing the second harmonic order pulse. Harmonic mode-locking is regarded as a phenomenon when a single circulating pulse breaks into multiple pulses with constant temporal spacing. This technique is often adopted for high repetition rates in multi-gigahertz fibre lasers [15]. The typical pulse train of the mode-locked fibre laser is shown in Fig. 7 for two different pump powers of 100 and 108 mW. The attainable pulse widths are 14.2 and 8.1 µs at 100 and 108 mW, respectively. The optical spectrum of the harmonic pulse is illustrated in Fig. 8, when the pump power is set at 125 mW. As shown in the figure, the harmonic laser operates at 1569.36 nm with peak output power of −18.4 dBm and 3 dB bandwidth of 1.7 nm.

Fig. 9 depicts the relationship between the output power and pump power for both DSR and harmonic pulses obtained from

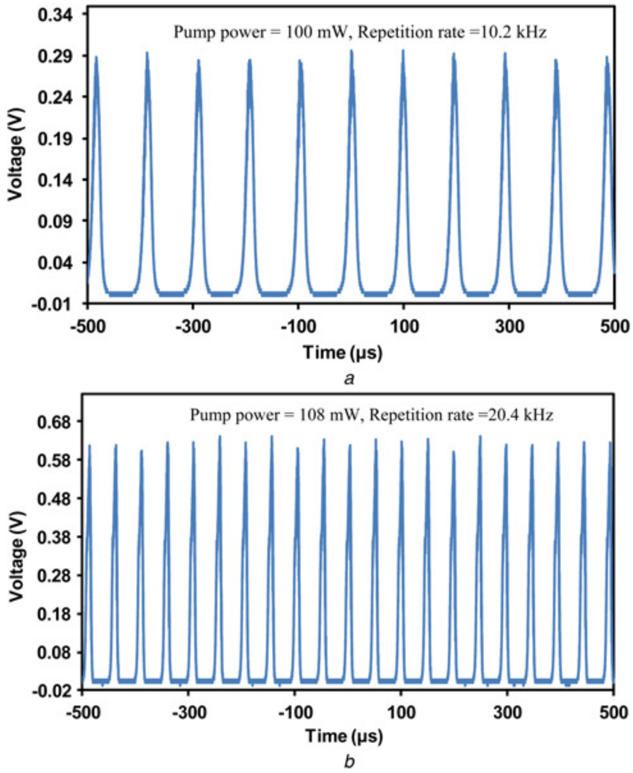

Fig. 7 *Typical pulse train of the mode-locking pulse at two different pump powers*
a 100 mW
b 108 mW

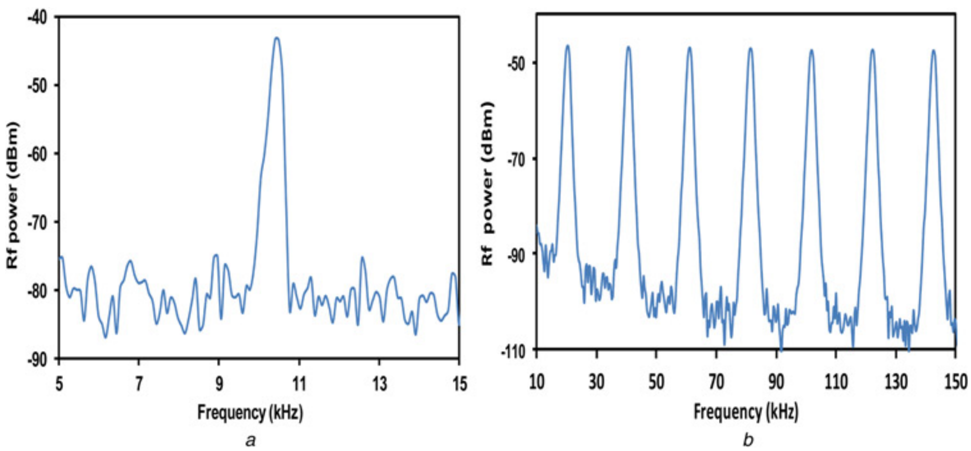

Fig. 6 *RF spectrum of the generated DSR pulses*
a Square
b Harmonic

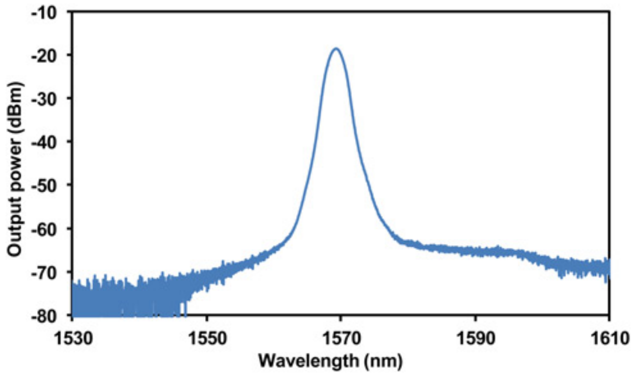

Fig. 8 *Output spectrum of the harmonic mode-locked EDFL*

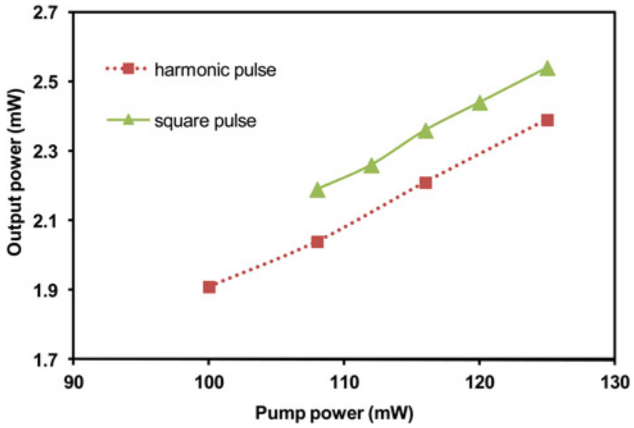

Fig. 9 *Measured output power for square and harmonic pulses at various pump powers*

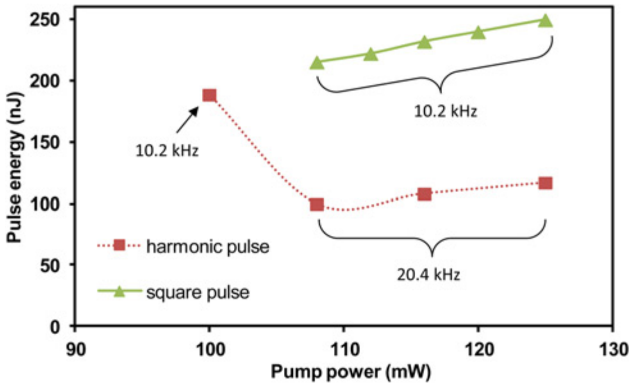

Fig. 10 *Pulse energy of produced pulse for square and harmonic pulses*

the proposed mode-locked erbium-doped fibre laser (EDFL) of Fig. 1. The output power is measured at the 50% port of second 3 dB coupler, which channels the output light into OSA. It is observed that the output power increases linearly with pump power for both lasers. As expected, the square pulse recorded higher output power compared with harmonic pulse. The output power for square pulse varies from 2.19 to 2.54 mW as the pump power increases from 108 to 125 mW. On the other hand, for harmonic pulse, the highest measured output power is 2.39 mW at a pump power of 125 mW. Fig. 10 shows how the pulse energy changes with the increment of pump power for both lasers. Both square and harmonic pulses exhibit relatively high pulse energy in the nano-Joule range because of the long cavity length used in the laser setup. Pulse energy of both lasers is found to be increasing with pump power. By increasing the pump power from 108 to 125 mW, the pulse energy of the square pulse increases from 215.3 to 249.8 nJ, whereas the pulse energy for the harmonic pulse improves from 0.215 to 0.249 pJ. It is observed that the pulse energy reduces drastically from 188.7 nJ (100 mW) to 100 nJ (108 mW) as the fundamental pulse breaks into the second harmonic order pulse. When the fundamental pulse breaks, the repetition rate doubles from 10.2 to 20.4 kHz. This will reduce the pulse energy as the pulse energy is inversely proportional to repetition rate. Consequently, the pulse energy of square pulse can be further increased by optimising the laser parameters and employing higher pump power.

The maximum attainable pulse energy for the square pulse is higher than second harmonic pulse by 53.1%. Lower pulse energy is observed for harmonic pulse because of the occurrence of pulse breaking phenomena, where a single pulse breaks into many pulses; two pulses in this experiment. After a single pulse is formed and traverses in the cavity, it encounters high non-linear effects and dispersion, introduced by the long SMF. A single pulse will break into many pulses where overtaking of different parts of a pulse will lead to optical wave breaking. It can be concluded that a laser should remain in single pulse operation in order to realise high pulse energy. Square pulse, which has steeper leading and trailing edges along with flat top in the temporal domain, can better withstand pulse breaking compared with the Gaussian or $sech^2$ shape pulse. It can be presumed that the square pulse has very low-frequency chirps across the central region of pulse and has non-linear pulse chirping at the pulse edges [16]. The non-linear chirp at the pulse edges can resist the dispersion and non-linearity effects in the cavity and thus can maintain its wave breaking free pulse.

Neither square pulse nor harmonic pulse is observed when the 20 km long SMF is removed. Without the long SMF, only the conventional pulse with Kelly side-bands is obtained. The insertion of 20 km long SMF brings the cavity's parameter near to the resonance curve, thereby producing wave breaking free square pulse. From the experimental results, the laser operates in two different operating regimes, harmonic and square pulse, by changing the pump power and also the polarisation of light. The change of light polarisation leads to different saturable absorption strength and intrinsic spectral filtering, which affects the intra-cavity non-linear gain and transmittivity. As a result, various kinds of pulse shapes can be formed. Both square and harmonic pulses generated by the mode-locked EDFL are stable. If there is no perturbation introduced to the laser, both square and harmonic pulses EDFL can last several hours under normal laboratory conditions.

4 Conclusion

A nanosecond square pulse laser source operating at 1568.7 nm with ultra-low repetition rate is demonstrated by inserting a 20 km long SMF in the ring cavity. A stable square pulse is obtained at the fundamental repetition rate of 10.2 kHz based on the NPR process. The pulse width can be easily tuned from 28.2 to 167.7 ns while maintaining almost constant peak power by increasing the pump power. Pulse energy as high as 249.8 nJ is recorded at the maximum pump power of 125 mW. This square pulse in nanosecond time scale is beneficial for numerous applications, especially in all optical square wave clocks for photonics integrated circuits and all optical signal processing. The DSR pulse can be switched to the harmonic pulse with a fixed repetition rate of 10.2 kHz by adjusting the PC. The pulse width of the harmonic pulse can be tuned from 14.2 to 8.08 μs as the pump power increases from 108 to 125 mW. Compared with the harmonic laser, the DSR can acquire higher non-linear effects without pulse breaking and therefore higher pulse energy could be delivered.

5 Acknowledgments

This project was funded by the Ministry of Education and University of Malaya under various grant schemes (grant no. D000009-16001 and PG068-2013B).

6 References

[1] Matsas V.J., Newson T.P., Zervas M.N.: 'Self starting passively mode-locked fiber ring laser exploiting nonlinear polarization switching', *Opt. Commun.*, 1992, **92**, (1–3), pp. 61–66

[2] Duan L., Liu X., Mao D., Wang L., Wang G.: 'Experimental observation of dissipative soliton resonance in an anomalous dispersion fiber laser', *Opt. Express*, 2012, **20**, (1), pp. 265–270

[3] Wang S.-K., Ning Q.-Y., Luo A.-I., Lin Z.-B., Luo Z.-C., Xu W.-C.: 'Dissipative soliton resonance in a passively mode-locked figure eight fiber laser', *Opt. Express*, 2013, **21**, (2), pp. 2402–2407

[4] Wu X., Tang D.Y., Zhang H., Zhao L.M.: 'Dissipative soliton resonance in an all normal dispersion erbium doped fiber laser', *Opt. Express*, 2009, **17**, (7), pp. 5580–5584

[5] Yang J., Guo C., Ruan S., Ouyang D., Lin H., Wu Y., Wen R.: 'Observation of dissipative soliton resonance in a net normal dispersion figure of eight fiber laser', *IEEE Photonics J.*, 2013, **5**, (3), p. 1500806

[6] Zhang X., Gu C., Chen G., *ET AL.*: 'Square wave pulse with ultra wide tuning range in a passively mode-locked fiber laser', *Opt. Lett.*, 2012, **37**, (8), pp. 1334–1336

[7] Wang L., Liu X., Gong Y., Mao D., Duan L.: 'Observation of four types of pulses in a fiber laser with large net normal dispersion', *Opt. Express*, 2011, **19**, (8), pp. 7616–7624

[8] Mao D., Liu X., Han D., Lu H.: 'Compact all fiber laser delivering conventional and dissipative solitons', *Opt. Lett.*, 2013, **38**, (16), pp. 3190–3193

[9] Han D.D., Liu X.M., Cui Y.D., Wang G.X., Zeng C., Yun L.: 'Simultaneous picoseconds and femtosecond solitons delivered from a nanotube mode-locked all fiber laser', *Opt. Lett.*, 2014, **39**, (6), pp. 1565–1568

[10] Liu X., Han D., Sun Z., *ET AL.*: 'Versatile multi-wavelength ultrafast fiber laser mode-locked by carbon nanotubes', *Sci. Rep.*, 2013, **3**, p. 2718

[11] Cui Y., Liu X.: 'Graphene and nanotube mode-locked fiber laser emitting dissipative and conventional solitons', *Opt. Express*, 2013, **21**, (16), pp. 18969–18974

[12] Chang W., Ankiewwicz A., Soto-Crespo J.M., Akhmediev N.: 'Dissipative soliton resonances', *Phys. Rev. A*, 2008, **78**, (2), p. 023830

[13] Chang W., Soto-Crespo J.M., Ankiewicz A., Akhmediev N.: 'Dissipative soliton resonances in the anomalous dispersion regime', *Phys. Rev. A*, 2009, **79**, (3), p. 033840

[14] Sotor J., Sobon G., Krzempek K., Abramski K.M.: 'Fundamental and harmonic mode locking in erbium doped fiber laser based on graphene saturable absorber', *Opt. Commun.*, 2012, **285**, (13), pp. 3174–3178

[15] Zhang Z.X., Zhan L., Yang X.X., Luo S.Y., Xia Y.X.: 'Passive harmonically mode-locked erbium doped fiber laser with scalable repetition rate up to 1.2 GHz', *Laser Phys. Lett.*, 2007, **4**, (8), pp. 592–596

[16] Liu X.: 'Mechanism of high energy pulse generation without wave breaking in mode-locked fiber lasers', *Phys. Rev. A*, 2010, **82**, (5), p. 053808