Journal of Visualized Experiments

Rapid Repetition Rate Fluctuation Measurement of Soliton Crystals in a Microresonator

--Manuscript Draft--

Article Type:	Invited Methods Article - JoVE Produced Video
Manuscript Number:	JoVE60689R1
Full Title:	Rapid Repetition Rate Fluctuation Measurement of Soliton Crystals in a Microresonator
Section/Category:	JoVE Engineering
Keywords:	Photonics; Integrated optics; Optical frequency comb; Repetition rate fluctuation
Corresponding Author:	Weiqiang Wang CHINA
Corresponding Author's Institution:	
Corresponding Author E-Mail:	wwq@opt.ac.cn
Order of Authors:	Weiqiang Wang
	Peng Xie
	Xinyu Wang
	Wenfu Zhang
	Zhizhou Lu
	Yang Wang
	Wei Zhao
Additional Information:	
Question	**Response**
Please indicate whether this article will be Standard Access or Open Access.	Standard Access (US$2,400)
Please indicate the **city, state/province, and country** where this article will be **filmed**. Please do not use abbreviations.	Xi'an Shaanxi Province China

TITLE:

Rapid Repetition Rate Fluctuation Measurement of Soliton Crystals in a Microresonator

AUTHORS AND AFFILIATIONS:
Peng Xie[1,2*], Xinyu Wang[1,2*], Weiqiang Wang[1,2], Wenfu Zhang[1,2], Zhizhou Lu[1,2], Yang Wang[1,2], Wei Zhao[1,2]

[1]State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics (XIOPM), Chinese Academy of Sciences (CAS), Xi'an, China
[2]University of Chinese Academy of Sciences, Beijing, China

*Authors contributed equally

Corresponding Authors:
Weiqiang Wang (wwq@opt.ac.cn)
Wenfu Zhang (wfuzhang@opt.ac.cn)

Email Addresses of Co-authors:
Peng Xie (xiepeng@opt.cn)
Xinyu Wang (wangxinyu2016@opt.cn)
Zhizhou Lu (luzhizhou2015@opt.cn)
Yang Wang (wangyang2017@opt.cn)
Wei Zhao (weiz@opt.ac.cn)

SUMMARY:
Here, we present a protocol to generate soliton crystals in a butterfly-packaged micro-ring resonator using a thermal tuned method. Further, the repetition rate fluctuations of a soliton crystal with a single vacancy are measured using a delayed self-heterodyne method.

ABSTRACT:
Temporal solitons have attracted great interest in the past decades for their behavior in a steady state, where the dispersion is balanced by the nonlinearity in a propagation Kerr medium. The development of dissipative Kerr solitons (DKSs) in high-Q microcavities drives a novel, compact, chip-scale soliton source. When DKSs serve as femtosecond pulses, the repetition rate fluctuation can be applied to ultrahigh precision metrology, high-speed optical sampling, and optical clocks, among other uses. In this paper, the rapid repetition rate fluctuation of soliton crystals (SCs), a special state of DKSs where particle-like solitons are tightly packed and fully occupy a resonator, is measured based on the well-known delayed self-heterodyne method. The SCs are generated using a thermal-controlled method. The pump is a frequency fixed laser with a linewidth of 100 Hz. The integral time in frequency fluctuation measurements is controlled by the length of the delay fiber. For a SC with a single vacancy, the repetition rate fluctuations are ~53.24 Hz within 10

μs and ~509.32 Hz within 125 μs, respectively.

INTRODUCTION:

The steady DKSs in microresonators, where the cavity dispersion is balanced by Kerr nonlinearity, as well as the Kerr gain and cavity dissipation[1], have attracted great interest in the scientific research community for their ultra-high repetition rate, compact size, and low cost[2]. In the time domain, DKSs are stable pulse trains that have been used for high-speed ranging measurement[3] and molecular spectroscopy[4]. In the frequency domain, DKSs have a series of frequency lines with equal frequency spacing that are suitable for wavelength-division-multiplex (WDM) communications systems[5,6], optical frequency synthesis[7,8], and ultra-low noise microwave generation[9,10], among other applications. The phase noise or linewidth of comb lines directly affects the performance of these application systems. It has been proven that all the comb lines have the same linewidth with the pump[11]. Therefore, using an ultra-narrow linewidth laser as a pump is an effective approach to improve the performance of DKSs. However, the pumps of most reported DKSs are frequency sweeping external cavity diode lasers (ECDLs), which suffer from relatively high noise and have a broad linewidth on the order of tens to hundreds of kHz. Compared with tunable lasers, fixed-frequency lasers produce significantly less noise, have narrower linewidths, and are smaller. For example, Menlo systems can provide ultra-stable laser products with a linewidth of less than 1 Hz. Using such a frequency fixed laser as a pump can significantly reduce the noise of the generated DKSs. Recently, microheater or thermoelectric cooler (TEC)-based thermal tuning methods that use frequency fixed lasers as pumps have been used for DKSs generation[12,13,14].

Repetition rate stability is another important parameter of DKSs. Generally, frequency counters are used to characterize the frequency stability of DKSs within a gate time, which is generally on the order of a microsecond to a thousand seconds[15,16]. Limited by the bandwidth of the photodetector and frequency counter, electro-optic modulators or reference lasers are typically used to lower the detected frequency when the free-spectral-range (FSR) of the DKSs is over 100 GHz. This not only increases the complexity of test systems, but also produces additional measurement errors caused by the stability of RF sources or reference lasers.

In this paper, a micro-ring resonator (MRR) is butterfly packaged with a commercial TEC chip that is used to control the operation temperature. Using a frequency fixed laser with a linewidth of 100 Hz as a pump, soliton crystals (SCs) are stably generated by manually decreasing the operating temperature; these are special DKSs that can completely fill a resonator with collectively ordered ensembles of copropagating solitons[17]. To the best of our knowledge, this is the narrowest linewidth pump in DKSs generation experiments. The power spectral density (PSD) spectrum of every comb line is measured based on a delayed self-heterodyne interferometer (DSHI) method. Benefitting from the ultra-narrow linewidth of the comb lines, the repetition rate instability of soliton crystals (SCs) is derived from the central frequency drift of the PSD curves. For the SC with a single vacancy, we obtained a repetition rate instability of ~53.24 Hz within 10 μs and ~509.32

Hz within 125 μs.

The protocol consists of several main stages: First, the MRR is coupled with a fiber array (FA) using a six-axis coupling stage. The MRR is fabricated by a high-index doped silica glass platform[18,19]. Then, the MRR is packaged into a 14-pin butterfly package, which increases the stability for the experiments. SCs are generated using a thermal-controlled method. Finally, the repetition rate fluctuations of SCs are measured by a DSHI method.

PROTOCOL:

1. Optical coupling

1.1. Polish the end-face of the MRR on a grinding plate using 1.5 µm abrasive powders (aluminum oxide) mixed with water for 5 min.

1.2. Fix the MRR with a chip fixture and place an eight-channel FA on a six-axis coupling stage, which includes three linear stages with a resolution of 50 nm and three angle stages with a resolution of 0.003°. The patches of the MRR and FA are 250 µm.

1.3. Use a 1,550 nm laser as an optical source for real-time monitoring of the coupling efficiency. Carefully adjust the position of the FA until the inset loss reaches the minimum value, typically less than 6 dB, corresponding to a coupling loss of less than 3 dB per facet.

1.4. Use an ultraviolet (UV) curved adhesive (**Table of Materials**) to glue the MRR and FA. Place the adhesive on the side edge of the contact surface, which ensures that there is no glue on the optical path.

1.5. Expose the UV-curved adhesive to a UV lamp for 150 s and bake in a chamber at 120 °C for more than 1 h.

2. Device packaging

2.1. Conglutinate a 10.2 mm x 6.05 mm TEC chip with a maximum power of 3.9 W to the baseplate of a standard 14-pin butterfly package using silver glue. Solder the two electrodes of the TEC chip to two pins of the butterfly package.

2.2. Paste a 5 mm × 5 mm × 1 mm tungsten plate to the surface of the TEC chip using silver glue. Use the tungsten plate as a heat sink to fill the gap between the TEC and MRR.

2.3. Paste the MRR device to the top of the tungsten plate using silver glue and fix the pigtail of the FA to the output port of the butterfly package.

2.4. Paste a thermistor chip to the surface of the TEC chip using silver glue. Connect one electrode of the thermistor to the top surface of TEC chip. Wire bond the other electrode of the thermistor and the top surface of TEC chip to two pins of the butterfly package using gold thread.

2.5. Bake the packaged device at 100 °C for 1 h to solidify the silver glue.

2.6. Seal the butterfly package. **Figure 1** shows the packaged device.

3. SCs generation

3.1. **Figure 2** shows the set-up of the experiments. Use an erbium-doped fiber amplifier (EDFA) to boost the pump for micro-comb generation. Control the polarization state of the pump using a fiber polarization controller (FPC). Connect all the devices using single mode fibers (SMF).

3.2. Fix the wavelength of the pump laser at 1,556.3 nm. Manually tune the operation temperature through an external commercial TEC controller.

3.3. Monitor the output optical spectrum with an optical spectrum analyzer. Detect the output power trace with a 3 GHz photodetector and record with an oscilloscope.

3.4. Set the output of the EDFA to 34 dBm, corresponding to an on-chip power of 30.5 dBm (considering the coupling loss of the MRR and FA, insert loss of the FPC), which ensures that there is enough power coupled into the MRR for micro-comb generation.

3.5. Set the thermistor to 2 kΩ, corresponding to an operating temperature of 66 °C. Then slowly decrease the operating temperature by changing the set value of the thermistor. In these experiments, when the thermistor was set to 5.8 kΩ, corresponding to 38 °C, one resonance of the MRR passed through the pump and a triangular shape power trace was recorded.

3.6. Tune the polarization of the pump by the FPC until an SC step is observed at the falling edge of the triangular transmission power trace. **Figure 3** shows a typical optical transmission power trace.

3.7. Slowly decrease the operation temperature from ~66 °C and stop when a palm-like optical spectrum is observed on the optical spectrum analyzer. The value of the thermistor was around 5.6 kΩ in these experiments. **Figure 4A** and **Figure 5B** show the optical spectra of perfect SCs and SCs with a single vacancy, respectively.

4. Repetition rate fluctuation measurement

4.1. Connect the generated SCs to a tunable bandpass filter (TBPF) to extract an individual comb line. Set the passband of the TBPF to 0.1 nm. Its central wavelength can be tuned over the full C and L band. The filter slope should be 400 dB/nm.

4.2. Couple the selected comb line to an asymmetric Mach-Zehnder interferometer (AMZI). The optical frequency in one arm of the AMZI is shifted by 200 MHz using an acousto-optic modulator (AOM). The optical field in the other arm is delayed by a segment of optical fiber. Delay fibers of 2 km and 25 km are used in these experiments.

4.3. Detect the output optical signal with a photodiode and analyze the PSD spectrum using an electrical spectrum analyzer.

4.4. Tune the central wavelength of the TBPF. Measure the PSDs of every comb line using the described method. **Figure 4B,C** shows the PSD spectra for comb lines S1 and S2 of perfect SCs with the 2 km and 25 km delay optical fibers, respectively.

4.5. Using the same method, measure the PSD curves of SCs with a vacancy. Record the 3 dB bandwidth of the PSD curve and linearly fit it piecewise as shown in **Figure 5B,C**. Repetition rate fluctuations of ~53.24 Hz within 10 µs and ~509.32 Hz within 125 µs were derived.

REPRESENTATIVE RESULTS:

Figure 3 shows the transmission power trace while a resonance thermal was tuned across the pump. There was an obvious power step that indicated the generation of SCs. The step had similar power compared with its precursor, the modulational instability comb. Therefore, the generation of SCs was not tuning speed dependent. The SCs exhibited a great variety of states, including vacancies (Schottky defects), Frenkel defects, and superstructure[12,17]. As examples, **Figure 4A** shows a perfect SC with 27 solitons and **Figure 5A** is a SC with a single vacancy.

The frequency of the μ^{th} comb line was equal to

$$f_{pump} + \mu * f_{rep}$$

and the frequency fluctuation of the μ^{th} comb line can be expressed as:

$$\Delta f_{\mu} = \Delta f_{pump} + \mu \cdot \Delta f_{rep}$$

where μ is the mode number away from the pump, f_{rep} is the repetition rate of the SCs, and Δf_{pump} and Δf_{rep} are the frequency fluctuations of the pump laser and the repetition rate of the SCs, respectively. Therefore, the repetition rate fluctuation of the SCs was almost amplified µ times at the μ^{th} frequency line.

For perfect SCs, **Figure 4B,C** shows the measured PSD spectra for the pump, S1 and S2, based on a 2 km and a 25 km delay fiber, respectively. The most notable features of the PSD curves were the flat tops, which were caused by the frequency fluctuation within the delay time. When the delay time was 10 µs, the frequency fluctuations of S1 and S2 were 2.08 kHz and 3.54 kHz, respectively. When the delay fiber was 25 km, the measured frequency fluctuations of S1 and S2 were 14.31 kHz and 28.02 kHz, respectively.

Figure 5A shows the typical optical spectrum of SC with a single vacancy. There were 27 solitons circulating in the MRR. The measured frequency fluctuations of each comb line were plotted and are shown in **Figure 5B,C**. The piecewise linear fitting lines are plotted in blue lines which can be expressed as

$$\Delta f_{2km} = 550 + 53.24 * \mu$$

$$\Delta f_{2km} = 1000 + 509.32 * \mu$$

The average slopes of the fitting lines were about 53.24 Hz/FSR and 509.32 Hz/FSR, which represent the repetition rate fluctuations of the SC within the responding delay times of 10 µs and 125 µs, respectively. The residual frequency fluctuations were regarded as the frequency fluctuation of the pump laser together with the frequency fluctuation of the driven radio signal of the AOM.

FIGURE LEGENDS:

Figure 1. Butterfly Packaged MRR. (**A**) Model and (**B**) picture of the butterfly packaged MRR.

Figure 2. The experimental setup of Kerr OFCs generation and repetition rate fluctuation measurement. The inset shows the optical spectrum of one typical SC with a single vacancy. A frequency fixed CW laser with a linewidth of 100 Hz was used as the pump. An EDFA was used to boost the pump up to 34 dBm. The frequency fluctuation was measured by the delayed self-heterodyne interferometer method. CW = continuous wave; EDFA = erbium-doped fiber amplifier; FPC = fiber polarization controller; TEC = thermoelectric cooler; MRR = micro-ring resonator; BPF = bandpass filter; AOM = acousto-optic modulator; PD = photodiode; ESA = electrical spectrum analyzer.

Figure 3. Optical transmission power trace at the drop port. A SC step that had similar power to its precursor is clearly obtained.

Figure 4. Perfect SC. (**A**) Measured optical spectrum of a perfect SC. The inset shows the uniformly distributed 27 solitons in the MRR. (**B**) Measured PSD curves of the pump, S1 and S2, with the 2 km delay fiber. (**C**) Measured PSD curves of the pump, S1 and S2, with the 25 km delay fiber. The flat-top PSD curve was caused by the rapid frequency fluctuation of the comb lines.

Figure 5. SC with a single vacancy. (**A**) Optical spectrum of SC with a single vacancy. The inset shows the soliton distribution in the MRR. (**B**) Frequency fluctuations with the 2 km delay fiber. The repetition rate fluctuation was about 53.24 Hz within 10 µs. The frequency fluctuation introduced by the pump laser and measurement system was about 500 Hz. (**C**) The repetition rate fluctuation with a 25 km delay fiber was about 626 Hz within 125 µs. The frequency fluctuation introduced by the pump laser and measurement system was about 1 kHz.

Figure 6. Theorical PSD of the photocurrent when the optical coherent length is larger than the relative delay time. The red line shows no central frequency fluctuation. The blue line presents the PSD with linear central frequency fluctuation.

DISCUSSION:

On-chip DKSs provide novel compact coherent optical sources and exhibit excellent application prospects in optical metrology, molecular spectroscopy, and other functions. For commercial applications, compact packaged micro-comb sources are essential. This protocol provides a practical approach to make a packaged micro-comb that benefits from the reliable, low coupling loss connection between the MRR and FA, as well as a robust thermal-controlled DKS generation method. Therefore, our experiments are no longer coupling stage dependent and exhibit excellent environmental adaptation. Meanwhile, the pump is a wavelength fixed laser that can be operated with narrower linewidths, produces significantly less noise, and is much smaller compared to tunable lasers. Therefore, the protocol is a promising approach to potential commercial applications of integrated high-performance on-chip DKSs sources.

The main limitation to obtaining a fully integrated SCs source is the high pump power, which needs an EDFA to boost it. However, given the progress of manufacturing techniques, an MRR capable of increasing signal by an order of magnitude should soon be available and the EDFA can be removed. Recently, DKSs have been realized on SiN MRR with very low pump power. Therefore, we believe that practical fully integrated DKS sources will be made in the near future.

The stability of the repetition rate is one of the most important parameters to evaluate the performance of OFCs. Generally, the repetition rate stability is measured using a frequency counter. However, the repetition rates of micro-combs are typically on the order of tens of GHz to THz, which is out of the bandwidth of frequency counters and photodetectors. Therefore, indirect methods, such as a reference laser source or a modulator, are usually used for repetition rate stability measurement, which increases the complexity of the measurement system. Our protocol provides a DSHI based repetition rate fluctuation measurement scheme, where high frequency components and ultra-stable reference sources are unnecessary. The system does not have an upper repetition rate limitation. Our system measures the accumulated frequency fluctuation during the delay time, while the frequency counter-based method tests the average value in a gate time. Therefore, our scheme is complementary to frequency counter-based repetition rate stability measurement systems.

The linewidth of the pump laser is essential for a DSHI based repetition rate fluctuation measurement scheme. When an optical field

$$\mathrm{E(t)} = E_0 e^{i[\omega_0 t + \emptyset(t)]}$$

is measured by a DSHI scheme, the PSD spectrum of the photocurrent can be expressed as:

$$S_s(\omega) = \frac{\alpha^2}{2} I_0^2 \frac{\frac{2}{\tau_c}}{\left(\frac{2}{\tau_c}\right)^2 + (\omega-\Omega)^2}\left\{1 - e^{-\frac{2\tau_d}{\tau_c}}\left[cos(\omega-\Omega)\tau_d + \frac{\frac{2}{\tau_c}}{\omega-\Omega}\sin(\omega-\Omega)\,\tau_d\right]\right\} + \frac{\pi}{2}\alpha^2 I_0^2 e^{-\frac{2\tau_d}{\tau_c}}\delta(\omega-\Omega)$$

where E_0 and ω_0 are the amplitude and angular frequency, respectively; $\emptyset(t)$ is the initial phase of the optical field; α is the power ratio of the two interference arms; I_0 is the input optical intensity; τ_d and τ_c are the relative delay time and the coherent time of the optical field, respectively; and Ω is the frequency shift of the AOM. When τ_c is greater than τ_d, the PSD will be the overlap of a beating signal and a Dirac function, as shown in **Figure 6** (red line). However, considering the frequency fluctuation of lasers, the optical field can be expressed as

$$\mathrm{E(t)} = E_0 e^{i[(\omega_0 + \Delta\omega)t + \emptyset(t)]}$$

where $\Delta\omega$ is the angular frequency fluctuation. For DSHI, an additional frequency shift is added. **Figure 6** (blue line) shows the calculated PSD spectrum, where the optical frequency is linearly changed 10 kHz during the delay time. In contrast, when τ_c is less than τ_d, the Dirac function will be negligible, and our scheme can no longer measure the repetition rate fluctuation of DKSs. Our scheme is not suitable for the DKSs generated using a pump laser with a linewidth on the order of tens of kHz. Fortunately, a laser with a linewidth of less than 1 Hz has been commercialized, and locked fixed-frequency lasers with a linewidth of less than 40 mHz have been made[20]. Therefore, our scheme provides a simple rapid repetition rate instability measurement method for micro-comb performance evaluation in the future.

DISCLOSURES:

The authors declare that they have no competing financial interests.

ACKNOWLEDGEMENTS:

This work was supported by the National Natural Science Foundation of China (NSFC) (Grant No. 61635013, 61675231, 61475188, 61705257,and 61805277), the Youth Innovation Promotion Association of CAS (No. 2016353), and Light of West China Program of CAS (XAB2017A09), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDB24030600).

REFERENCES:

1. Herr T. et al. Temporal solitons in optical microresonators. *Nature Photonics*. **8**, 145–152 (2014).
2. Li, J., Lee, H., Chen, T., Vahala, K. J. Low-pump-power, low-phase-noise, and microwave to millimeter-wave repetition rate operation in microcombs. *Physical Review Letters*. **109**, 1–5 (2012).
3. Trocha, P. et al. Ultrafast optical ranging using microresonator soliton frequency combs. *Science*. **359**, 887–891 (2018).
4. Myoung-Gyun, S., Qi-Fan, Y., Ki Youl, Y., Xu, Y., Kerry, L. V. Microresonator soliton dual-comb spectroscopy. *Science*. **354**, 600–603 (2016).
5. Marin-Palomo P. et al. Microresonator-based solitons for massively parallel coherent optical communications. *Nature*. **546**, 274–279 (2017).
6. Fang-Xiang, W. et al. Quantum key distribution with dissipative Kerr soliton generated by on-chip microresonators. *arXiv*. 1812.11415 (2018).
7. Spencer, D. T. et al. An optical-frequency synthesizer using integrated photonics. *Nature*. **557**, 81–85 (2018).
8. Del'Haye, P. et al. Phase-coherent microwave-to-optical link with a self-referenced microcomb. *Nature Photonics*. **10**, 516–520 (2016).
9. Huang, S. W. et al. A broadband chip-scale optical frequency synthesizer at 2.7×10^{-16} relative uncertainty. *Science Advance*. **2**, e1501489 (2016).
10. Liang, W. et al. High spectral purity Kerr frequency comb radio frequency photonic oscillator. *Nature Communications*. **6**, 7957 (2015).
11. Liao, P. C. et al. Dependence of a microresonator Kerr frequency comb on the pump linewidth. *Optics Letters*. **42**, 779–782 (2017).
12. Wang, W. Q. Robust soliton crystals in a thermally controlled microresonator. *Optics Letters*. **43**, 2002–2005 (2018).
13. Chaitanya, J. et al. Thermally controlled comb generation and soliton modelocking in microresonators. *Optics Letters*. **41**, 2565–2568 (2016).
14. Lu, Z. Z. et al. Deterministic generation and switching of dissipative Kerr soliton in a thermally controlled micro-resonator. *AIP Advances*. **9**, 025314 (2019).
15. Jost, J. D. et al. Counting the Cycles of Light using a Self-Referenced Optical Microresonator. *Optica*. **2**, 706–711 (2014).
16. Brasch, V. et al. Self-referenced photonic chip soliton Kerr frequency comb. *Light: Science & Applications*. **6**, e16202-6 (2017).
17. Cole, D. C. et al. Soliton crystals in Kerr resonators. *Nature Photonics*. **11**, 671–676 (2017).
18. Little, B. E. A VLSI photonics platform. *Conference on Optical Fiber Communication*. **86**, 444–445 (2003).
19. Wang, W. Q. et al. Dual-pump kerr micro-cavity optical frequency comb with varying FSR spacing. *Scientific Report*. **6**, 28501 (2016).
20. Kessler, T. et al. A sub-40-m Hz-linewidth laser based on a silicon single-crystal optical cavity. *Nature Photonics*. **6**, 687–692 (2012).

Figure 1

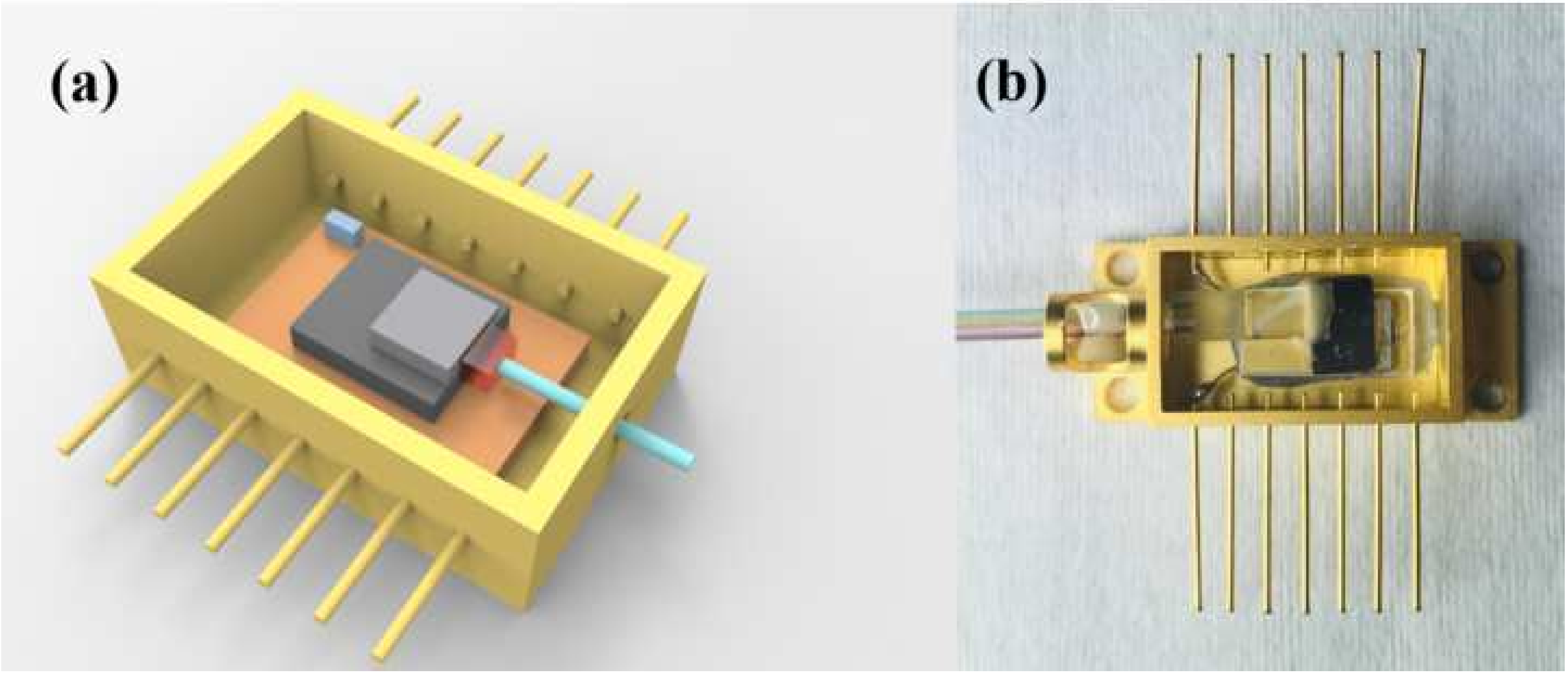


Figure 2 Click here to access/download;Figure;Fig.2.png

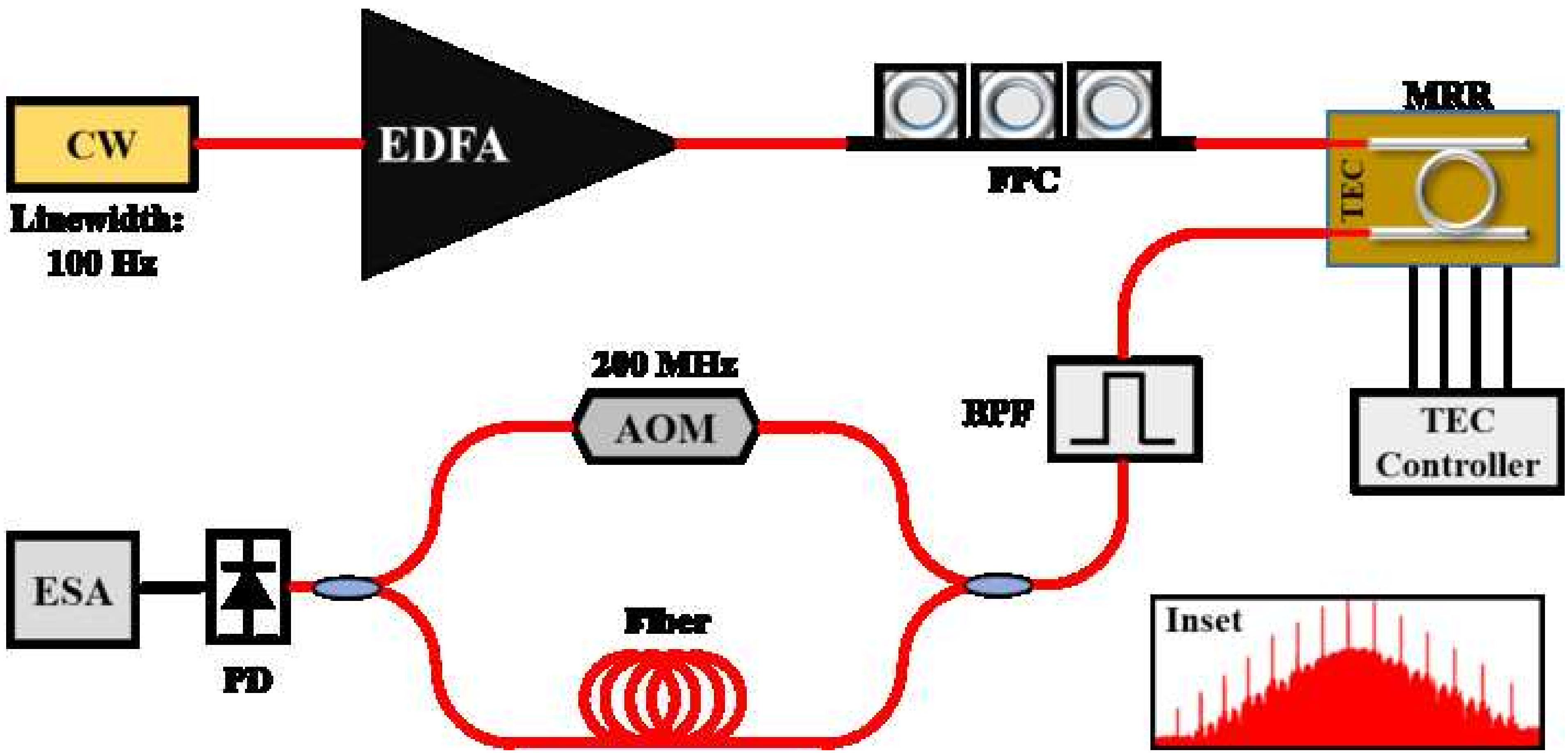


Figure 3

Click here to access/download;Figure;Fig.3.png

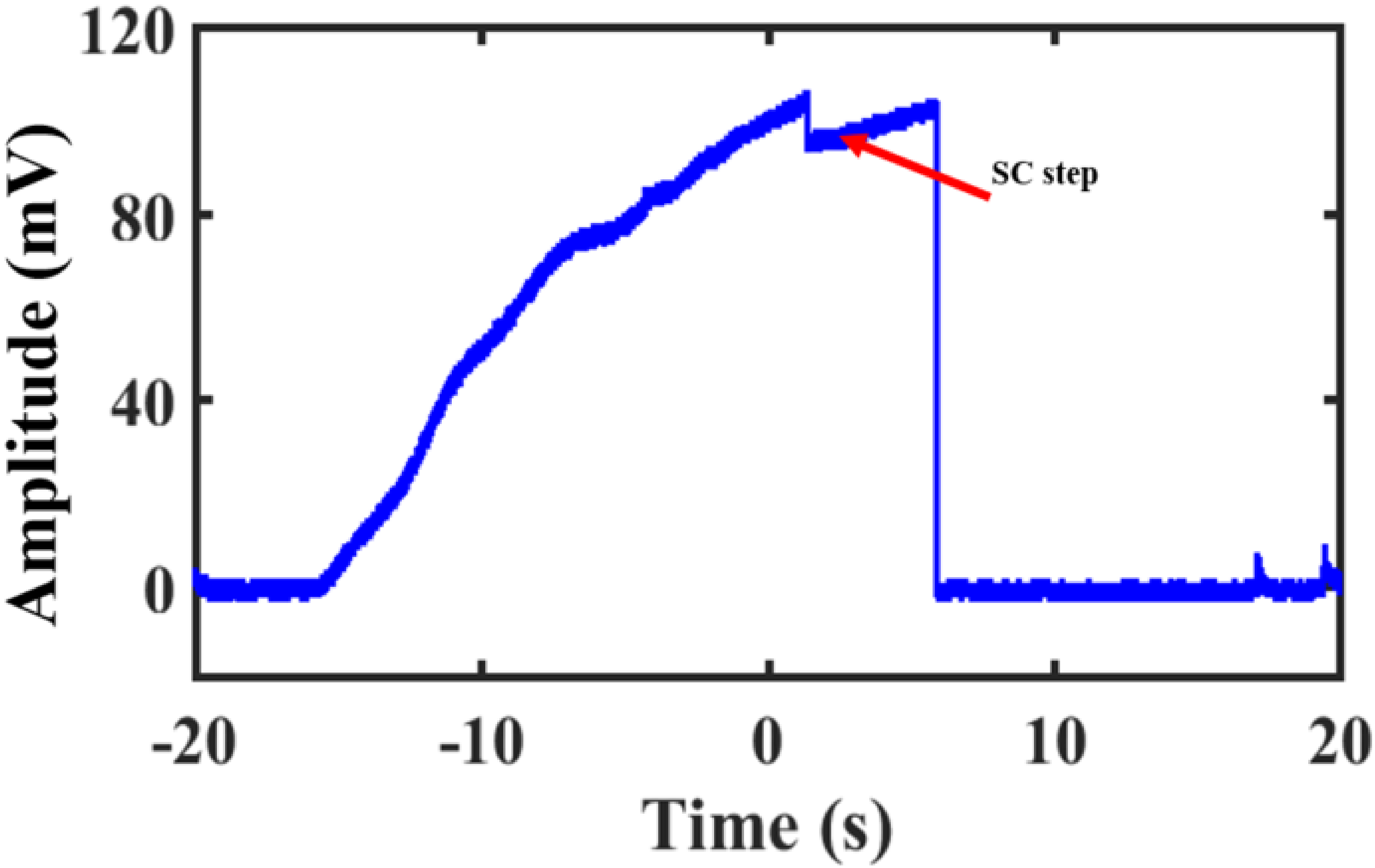


Figure 4

Click here to access/download;Figure;Fig.4.png

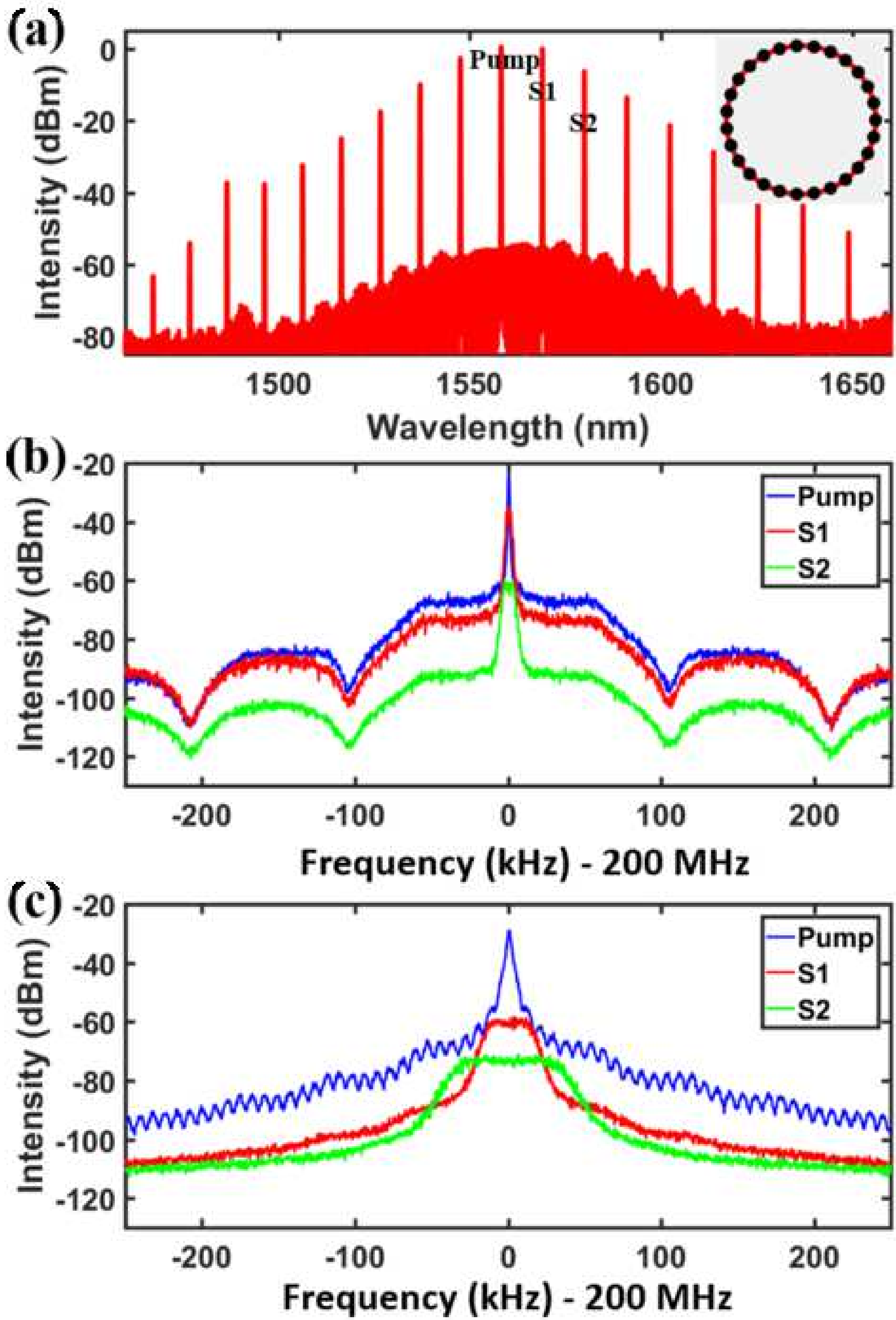


Figure 5

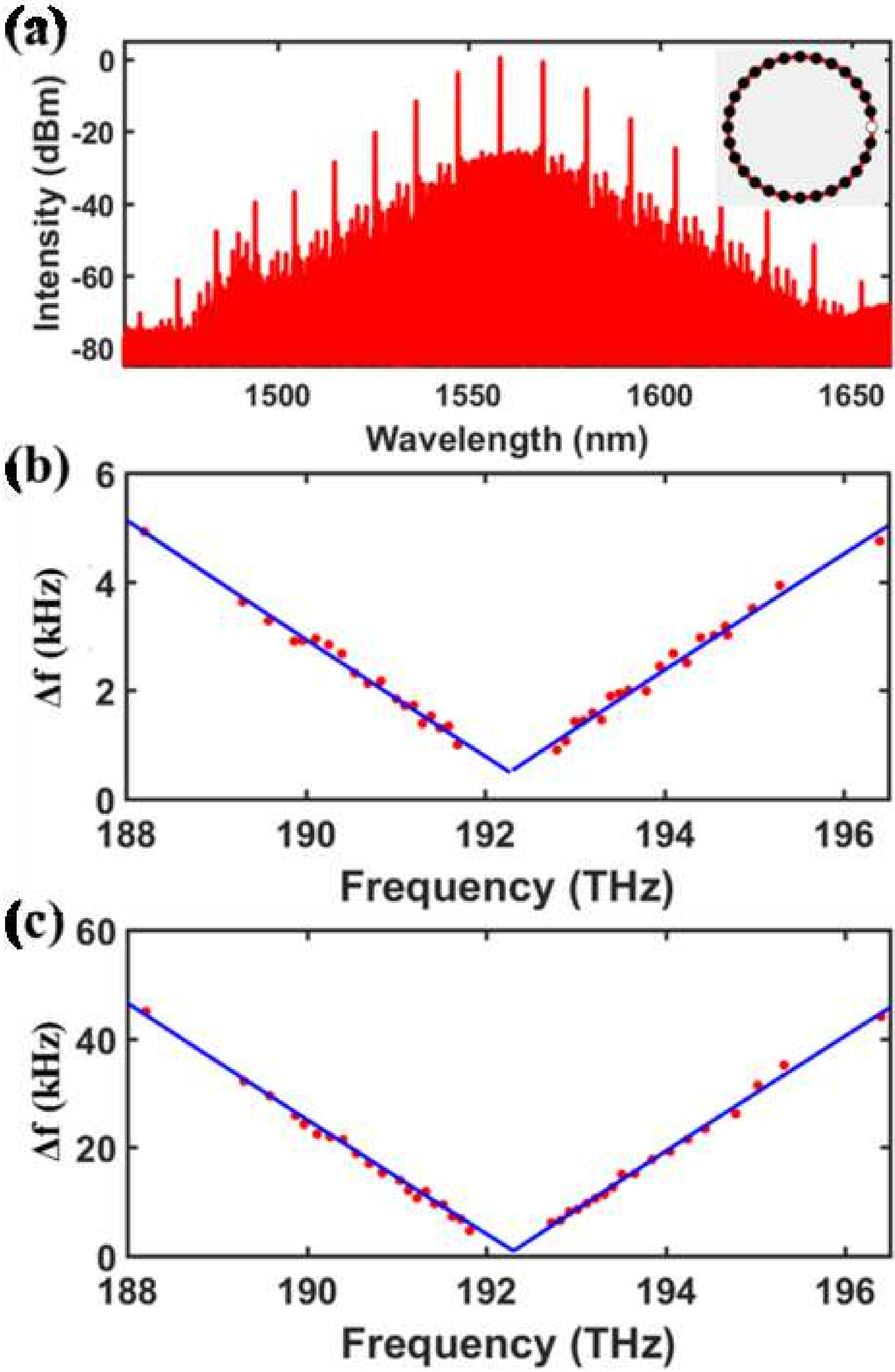
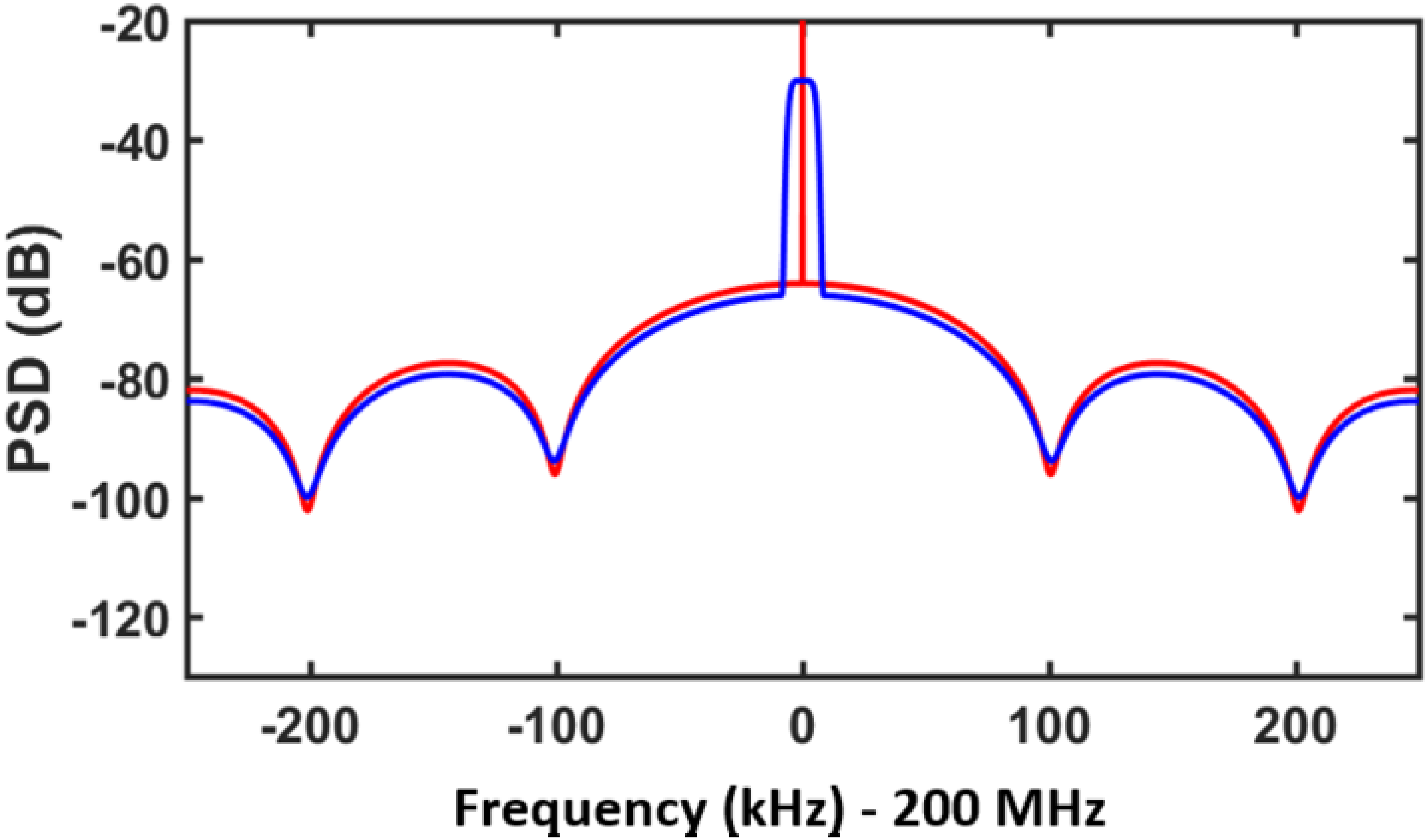

(a)
Intensity (dBm)
0
-20
-40
-60
-80
1500
1550
1600
1650
Wavelength (nm)
(b)
Δf (kHz)
6
4
2
0
188
190
192
194
196
Frequency (THz)
(c)
Δf (kHz)
60
40
20
0
188
190
192
194
196
Frequency (THz)

Figure 6


-20
-40
-60
-80
-100
-120
PSD (dB)
-200
-100
0
100
200
Frequency (kHz) - 200 MHz

Name of Material/Equipment	Company	Catalog Number
6-axis coupling stage	Suruga Seiki	KXC620G KGW060
Abrasive powder	Shenyang Kejing Auto-Instrument Co., LTD	2980002
Glue 3410	Electronic Materials Incorporated	Optocast 3410
High-index doped silica glass	Home-made	-
Pump laser	NKT Photonics	E15
Ultrastable Laser	Menlosystems	ORS

Comments/Description

Contains 3 linear motorized translation states and 3 angular motorized rotational stages.

Linear state: Minimum stepping: 0.05 µm; Travel: 20mm; Max.speed: 25mm/s; Repeatability: +/-0.3 µm; Rotational stage:Travel: ±8°; Resolution/pulse: 0.003 degree; Repeatability:±0.005°

Silicon carbide, granularity: 1.5 µm

Optocast 3410 is an ultra violet light and heat curable epoxy suitable for opto-electronic assembly. It cures rapidly when exposed to U.V. light in the 320-380 nm.

The MRR is fabricated by a high index doped silica glass platform. The waveguide section is 2×3 µm and radius is 592.1 µm, corresponding to FSR of 49 GHz.

It is a continuous wave fiber laser with linewidth of 100 Hz.

State-of-the-art linewidth (<1Hz) and stability (<2 x 10^{-15} Hz)

Authors' reply to comments on"Rapid Repetition Rate Fluctuation Measurement of Soliton Crystals in a Microresonator" by Peng Xie, Xinyu Wang et al.)

The authors appreciate the reviewer's valuable comments very much. The reviewer's comments are considered seriously and our manuscript has been revised carefully in accordance with reviewer's comments where possible.

Our replies to the comments are demonstrated as follows:

(**The blue content is the comments, the black content is the reply and the red content is the revised parts in the manuscript.**)

Editorial comments:

General:

1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues.

Our Reply: Thanks for the editor's valuable comments. We have checked and re-written some parts of the manuscript. Please refer to the revised manuscript.

1. Please ensure that the manuscript is formatted according to JoVE guidelines – letter (8.5" x 11") page size, 1-inch margins, 12 pt Calibri font throughout, all text aligned to the left margin, single spacing within paragraphs, and spaces between all paragraphs and protocol steps/substeps.
2. For in-text formatting, corresponding reference numbers should appear as numbered superscripts (without braces) after the appropriate statement(s).

Our Reply: We have revised the format of the manuscript, which has match to the JoVE guidelines.

Summary:

1. Please include a separate Summary section (before the abstract) that clearly describes the protocol and its applications in complete sentences between 10 and 50 words, e.g., "Here, we present a protocol to …

Our Reply: We have added a separate summary section before the abstract.

"**Summary:** Here, we present a protocol to realize soliton crystals generation in a butterfly packaged micro-ring resonator using thermal tuned method. Further, the repetition rate fluctuations of soliton crystals with a single vacancy are measured using a delayed self-heterodyne method."

Protocol:

1. There is a 10 page limit for the Protocol, but there is a 2.75 page limit for filmable content. If revisions cause the highlighted portion to be more than 2.75 pages, please highlight 2.75 pages or less of the Protocol (including headers and spacing) that identifies the essential steps of the

protocol for the video, i.e., the steps that should be visualized to tell the most cohesive story of the Protocol.

2. Please add more details to your protocol steps. Please ensure you answer the "how" question, i.e., how is the step performed? Alternatively, add references to published material specifying how to perform the protocol action. If revisions cause a step to have more than 2-3 actions and 4 sentences per step, please split into separate steps or substeps.

Our Reply: Thanks for the editor's valuable advice. We have revised the section of Protocol and add more details. Please refer to protocol part of the revised manuscript.

Specific Protocol steps:

1. 1.1: What abrasive powders are used here? There is no information in the Table of Materials.

1, 2: Please provide more detail about gluing (e.g., exact positioning of the components).

Our Reply: We have added the detail information of abrasive powders and glue in the Table of Materials. The abrasive powders is from Shenyang Kejing Auto-Instrument Co., LTD. It is silicon carbide and its granularity is 1.5 μm.

The glue of 3410 (Optocast 3410) is an ultra violet light Cured Adhesive which is a common glue for opto-electronic assembly. It is solidified rapidly when exposed to U.V. light in spectrum rang of 320-380 nm. It is highly purified with a maximum ionic content of 10 ppm total Na+, K+ and Cl-. Optocast 3410 features ULTRA low shrinkage upon cure and is ideal for fixturing and aligning optical devices with less than 1-micron movement throughout its service life.

Figures:

1. Please remove the embedded figures from the manuscript. Please upload each Figure individually to your Editorial Manager account as a .png, .tiff, or .pdf file (6 files in total).
2. Please cite Figure 6 outside of the Figure legends.
3. Figure 4, 6: Please use '200 MHz' (include a space).

Our Reply: We will follow the comments, remove the embedded figures from manuscript and upload each Figure individually. We have cited Figure 6 outside of the Figure legends and have revised the 200MHz to 200 MHz, while there is a space between 200 and MHz. As is shown in following picture:

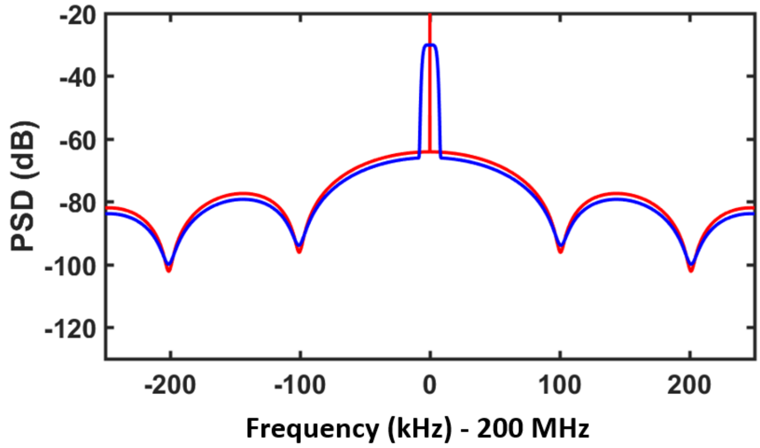


Figure 6. Theorical PSD of the photocurrent when the optical coherent length is larger than the relative delay time. Red line shows the case of without central frequency fluctuation. Blue line presents the PSD with linear central frequency fluctuation.

Discussion:

As we are a methods journal, please revise the Discussion to explicitly cover the following in detail in 3 – 6 paragraphs with citations:

a) Critical steps within the protocol
b) Any modifications and troubleshooting of the technique
c) Any limitations of the technique
d) The significance with respect to existing methods
e) Any future applications of the technique

Our Reply: Thanks for the editor's valuable advice, we have re-written the section of discussion. Please refer to the revised manuscript.

References:

1. Please ensure that the references appear as the following: [Lastname, F.I., LastName, F.I., LastName, F.I. Article Title. Source. Volume (Issue), FirstPage – LastPage (YEAR).] For more than 6 authors, list only the first author then et al.
2. Please do not abbreviate journal titles.

Our Reply: We have revised the References according to the comments. As is shown in following:

[1] Herr T. et al. Temporal solitons in optical microresonators. *Nature Photonics* **8**, 145–152 (2014).
[2] Li J., Lee H., Chen T., and Vahala K.J. Low-pump-power, low-phase-noise, and microwave to millimeter-wave repetition rate operation in microcombs. *Physical Review Letters* **109**, 1–5 (2012).
[3] Trocha P. et al. Ultrafast optical ranging using microresonator soliton frequency combs. Science 359, 887-891 (2018).

....

Table of Materials:

1. Please ensure the Table of Materials has information on all materials and equipment used, especially those mentioned in the Protocol.

Our Reply: We have added a Table of Materials.

Comments of the reviewer 1:

The manuscript is a description of the protocol for generating solitons in WGMs. The topic is highly interesting and it deserves publication but not in the present form.

Major Concerns:

It's very difficult to understand what the authors are proposing. There are a lot of sentences that are very dark and difficult to follow, the reading is not fluid. The introduction is too short. The protocol is far from being clear, for instance the fabrication of micro-ring resonator is never mentioned, I do not know which kind of glue is "the glue of 3410". The TEC is outside or inside the butterfly mount? Could you please show a picture of the inside of the package. The optical coupling and the device packaging are very difficult to understand. The manuscript should be revised carefully and be rewritten in a better way.

Our Reply: Thanks for the reviewer's valuable comments. The manuscript has been re-written. Please refer to the revised manuscript.

The fabrication of micro-ring resonator is out of the theme of this manuscript. Please refer to the references which have described the details of fabrication.

The glue of 3410 (Optocast 3410) is an ultra violet light Cured Adhesive which is a common glue for opto-electronic assembly. It is solidified rapidly when exposed to U.V. light in spectrum rang of 320-380 nm. It is highly purified with a maximum ionic content of 10 ppm total Na+, K+ and Cl-. Optocast 3410 features ULTRA low shrinkage upon cure and is ideal for fixturing and aligning optical devices with less than 1-micron movement throughout its service life.

The TEC chip is inside the butterfly mount. A picture of package is shown in Fig .1.

We added the details of the optical coupling and the device packaging. We appriciate the reviewer's valuable suggestion again. The whole manuscript has been rewritten. Please refer to the revised manuscipt.

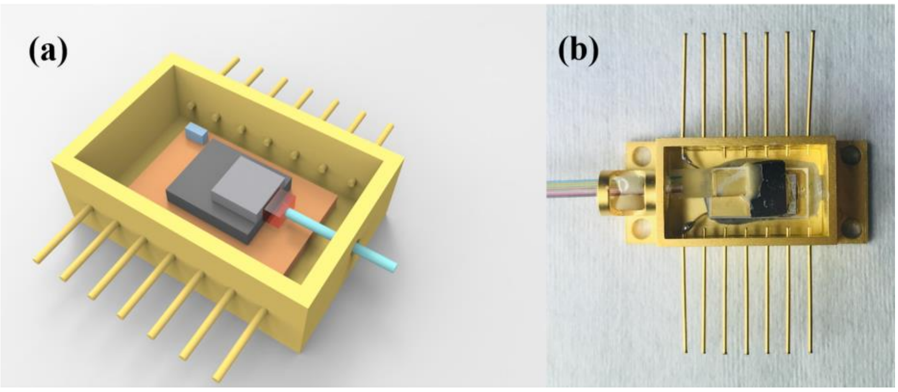


Figure 1. (a)The model and (b) image of the butterfly packaged MRR.

Minor Concerns:

Some conclusions could be helpful to summarize your results.

Reply: We has added a summary section in the revised manuscript. Please refer to the revised manuscript.

Comments of the reviewer 2:

This manuscript by Xie et. al., present the protocol for the measurement of repetition rate fluctuation of soliton crystal generated in a microresonator, using a delayed self-heterodyne method. The authors presented a method for packaging microresonator within a butterfly enclosure, which will be of great help for the practical application of Kerr frequency combs. Also, the measurement of comb line fluctuations seem effective. Thus I recommend publication of this manuscript.

Major Concerns:

MAJOR:

#1 As a method paper, the manuscript should present a clearer description about how the measured PSD be converted to frequency fluctuation (linewidth) of each comb line (maybe an analytical formula should be given)

Our Reply: Thanks for the reviewer's valuable comments. The linewidth of the pump laser is essential for the delayed self-heterodyne based repetition rate fluctuation measurement scheme. When an optical field $\mathrm{E(t)} = E_0 e^{i[\omega_0 t + \emptyset(t)]}$ is measured by the delayed self-heterodyne scheme, the PSD of the photocurrent is expressed as:

$$S_s(\omega) = \frac{\alpha^2}{2} I_0^2 \frac{\frac{2}{\tau_c}}{\left(\frac{2}{\tau_c}\right)^2 + (\omega - \Omega)^2} \left\{ 1 - e^{-\frac{2\tau_d}{\tau_c}} [cos(\omega - \Omega)\tau_d + \frac{\frac{2}{\tau_c}}{\omega - \Omega} \sin(\omega - \Omega)\tau_d] \right\} + \frac{\pi}{2} \alpha^2 I_0^2 e^{-\frac{2\tau_d}{\tau_c}} \delta(\omega - \Omega) \quad (4)$$

Where τ_d and τ_c are the relative delay time and the coherent time of the optical field respectively. Ω is frequency shift of the AOM. When τ_c is larger than τ_d, the PSD will be the overlap of a beating signal and a dirac function, as shown in Fig. 6 (red line). However, considering the frequency fluctuation of lasers, the optical field can be expressed as $\mathrm{E(t)} = E_0 e^{i[(\omega_0 + \Delta\omega)t + \emptyset(t)]}$, where $\Delta\omega$ is the angular frequency fluctuation. For DSHI, it is equivalent that an additional frequency shift is added. Figure 6 (blue line) shows the calculated PSD curve when the optical frequency is linearly changed 10 kHz during the delay time.

#2 MAJOR: to demonstrate the efficacy for device packaging, the structures and images of MRR, TEC, fiber array, and tungsten plate inside the butterfly enclosure must be illustrated.

Our Reply: To demonstrate the relative location of these components, a picture of the packaged device is added as shown in Fig. 1, where a TEC chip, MRR, FA and tungsten plate is plate in the butterfly package. An outside TEC controller is used to control the operation temperature of the device.

Minor Concerns:

#1: The detailed temperature change of the TEC to access the soliton crystal states should be given. Also, while changing the temperature of MRR using TEC, did the optical coupling also change? Maybe the on-chip pump power was smaller than 34 dBm?

Our Reply: Thanks for the viewer's comments. We have add the detail in the section of SCs generation. As is following:

1. Set the output of the EDFA to 34 dBm, corresponding the on-chip power of 30.5 dBm (considering the coupling loss of the MRR and FA, insert loss of the FPC), which ensures that there is enough power coupled into the MRR for micro-comb generation.
2. The thermistor is set to 2 kΩ, corresponding to operation temperature of 66 degrees. Then the operation temperature is slowly decreased by changing the set value of the thermistor. In our experiments, when the thermistor is set to 5.8 kΩ, corresponding to 38 degrees, one resonance of the MRR is passed through the pump and a triangular shape power trace is recorded.

Thanks very much!

Best regards,
Peng Xie, Xinyu Wang et al.