Observation of regular pulse train in a narrow-band optoelectronic oscillator*

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We have experimentally observed a new operating state of a regular pulse train in a narrow-band optoelectronic oscillator (OEO) system, where the direct-current (DC) bias of the Mach-Zehnder modulator is set at the maximum value of the transmission transfer function instead of the usual quadrature point. The observed quasi-steady-state pulse train is distinctly periodic, with a period of 10.5 μs and a center frequency of 10 GHz, and resembles a mode-locked OEO in its waveform. The formation of regular pulses here may arise from the dynamic balance of nonlinearity and narrow-band filter effects, with the transient characteristics of the pulses arising mainly from instabilities between the gain and cavity loss. Our results are of great importance for deepening the understanding of the nonlinear dynamical processes in OEO systems.

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Optoelectronic oscillators (OEOs) have received a lot of attention since their introduction because of the superior phase noise level of the generated microwave signals. For some time, the focus of OEOs' research has been on how to obtain continuous microwave signals with ultra-low phase noise. However, this means that the system needs to have a longer fiber length and smaller mode spacing. Therefore, pre-OEOs research mainly considered how to better achieve single-mode selection and system stability through oscillator improving topological architecture or new methods, including coupled-loop[1], multi-loop structures[2], parity-time symmetry[3], injection locking[4], phase-locked control[5], and other methods[6,7].

Until recently, attention has not been paid to multimode control and manipulation in OEOs. In terms of multimode coherent control, two different schemes of multimode time-domain control and Fourier-domain mode control have been studied and implemented, respectively. For the time-domain mode-locking aspect has caused a research boom, successively through the passive[8] and active way[9,10] to achieve a coherent superposition of multiple longitudinal mode oscillations in the resonant cavity of OEOs, thus generating a new type of low-noise microwave pulse signal in the form of solitons in the time domain waveform. At the same time, rational harmonic mode-locked OEOs[11] and self-regenerative mode-locked OEOs[12] further reveal new phenomena and new methods of multimode control, and continuously expand the direction of OEOs' research. Fourier-domain mode-locking[13,14] can be considered as a frequency-domain mode-locking technique, which has the advantage of breaking the limitation of the mode establishment time and greatly improving the frequency scanning speed of OEOs.

On the other hand, OEOs belong to a time-delayed nonlinear dynamical system, in which there are complex nonlinear processes such as bifurcation, stability solution, chaotic behavior[7,15-17], and other phenomena. The study of complex nonlinear processes will contribute to practical applications, such as high-performance microwave pulse generation, radar ranging, chaotic communication and ranging[7]. But until now, there are still many physical problems in this area that have yet to be studied. A typical example is the recently proposed microwave photon soliton in OEOs[18] with spontaneous frequency hopping, which is thought to be a new type of soliton caused by the oscillatory mode of interaction. However, the solitons found there are not solitons in the conventional sense, because it is not an envelope of a soliton shape in the time domain, nor is it a frequency comb distribution in the frequency domain. Therefore, it would be very interesting to realize the conventional soliton-like state in OEO systems by using the nonlinear phenomenon.

In conventional OEOs, the direct-current (DC) bias voltage of the Mach-Zehnder modulator (MZM) is generally fixed in the linear region for reliable operation and

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system simplicity, thus avoiding the complex effects of nonlinear processes. Nevertheless, in this work, we set the DC bias point near the maximum point of the MZM transfer function, which will produce a severe nonlinear gain mechanism and exhibit a special function similar to the pulse compression of saturable absorbers. At the same time, the narrow bandwidth microwave filter in the OEO loop compresses the frequency spectrum, which is equivalent to the dispersion effect of pulse broadening in the time domain. In this work, by carefully adjusting the balance of gain and loss of the system, we succeeded in observing the regular pulse waveforms of fundamental and harmonics regular pulse states experimentally. The OEO is a test bed for studying time-delayed nonlinear dynamics, and our experimental work studied here will stimulate more relevant theoretical studies that will contribute to further understanding of nonlinear dynamical effects in narrow-band OEOs.

The schematic diagram of the OEO experimental setup is illustrated in Fig.1(a), which is a positive time-delay feedback loop consisting of a laser diode (LD), a variable optical attenuator (VOA), an MZM, a long polarization-maintaining (PM) fiber, a photodetector (PD), a bandpass filter (BPF), two electronic amplifiers (EA1 and EA2), and an electrical power divider. For the operation of OEO, a continuous-wave light with a power of 20 dBm at 1 550 nm is generated by a narrow linewidth laser (EM650, Gooch & Housego) and is sent to an MZM (MXAN-LN-20, iXblue) with $V_{\pi,\mathrm{RF}}$=5 V biased at a fixed DC level after being attenuated by a VOA (VOA 50PM-APC, Thorlabs). Then, the intensity-modulated light passes through a spool of PM single-mode fiber (PM1550-XP, Thorlabs) with a length of 2.2 km and is converted into the microwave signal by a 20 Gbit/s PD (DSC50S, Discovery Semiconductors) based on InGaAs PIN photodiode. After being filtered by a home-made BPF with a center frequency of 10 GHz, the signal is amplified by a home-made EA1 with a gain of 25 dB, a 3 dB amplification spectrum of 8—12 GHz. Then, the output signal of the EA1 is amplified by another commercial driver EA2 (DR-AN-20-MO, iXblue) and is fed back into the MZM through a three-way power divider. Finally, the outputs of the divider are used for measuring the time and frequency domains of generated signal, respectively.

The MZM and BPF are two very important components for our experiment, so we first measured their characteristics respectively. Fig.1(b) shows the measured transfer function curve of our MZM with $V_{\pi,\mathrm{DC}}$=6 V, from which it can be seen that there is a sinusoidal oscillation of the transmittance with the DC bias voltage. So, the system will accordingly display a variety of different dynamical behaviors depending on the setting point of MZM. Generally, for the operation of OEO, the MZM is biased at the quadrature point q but not extreme value points as denoted by min or max in Fig.1(b). In the latter case, the MZM may promote the generation of pulses or chaos-like states[8,15]. And the measured S_{21} parameter of the BPF using a vector network analyzer is shown in Fig.1(c). We found that the BPF has a very narrow 3 dB bandwidth of about 8 MHz and about 3 dB insertion loss. Physically, the filter has the effect of compressing the frequency spectrum, thus broadening the pulse from the time domain. Therefore, a regular pattern pulse state can be expected when the gain and loss as well as nonlinear gain and linear filtering effect of the OEO cavity balance simultaneously.

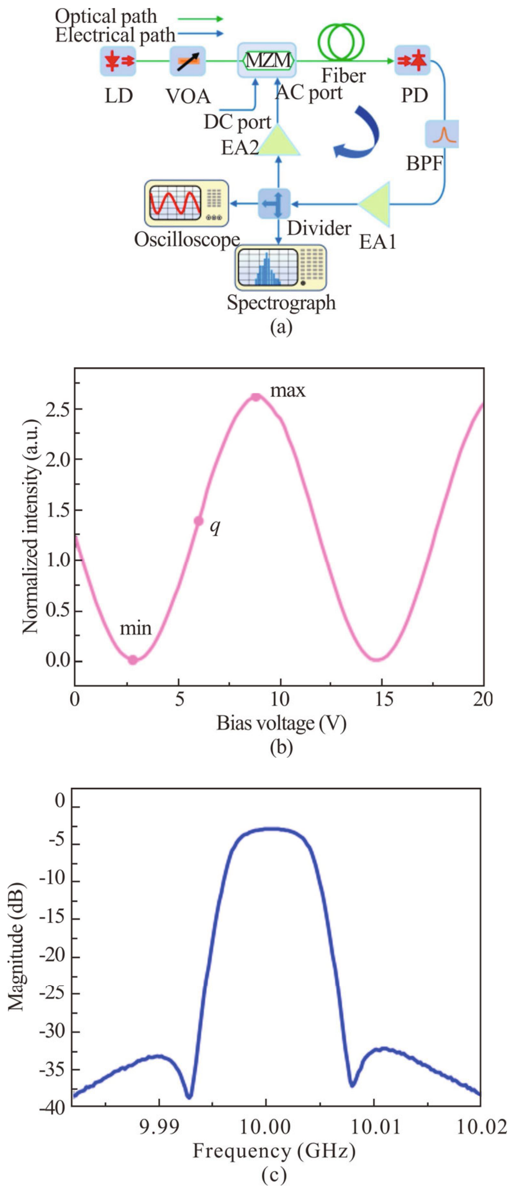
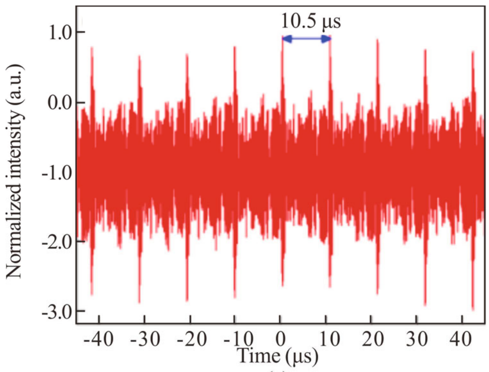
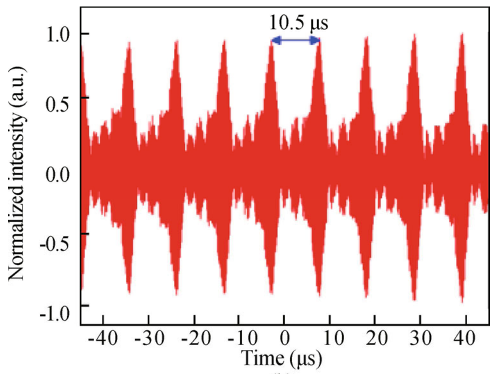


Fig.1 (a) Schematic diagram of the OEO; (b) Measured intensity modulator transfer function; (c) Measured frequency response of 10 GHz microwave band filter

Firstly, we started by setting the DC bias of 6.1 V around the q point, where we observed a continuous microwave signal generation with a center frequency of 10 GHz and phase noise of −131 dBc/Hz at 10 kHz offset. This indicates that the narrow BPF results in only a single longitudinal mode in the OEO loop. Despite the narrow filter bandwidth, the center frequency of the generated microwave signal is slightly different each time due to mode competition. After that, the biased voltage is changed to about 8.5 V, where the signal transmission of the MZM is close to its maximum value as denoted by max in Fig.1(b). At this time, by tuning the power of the light via the VOA, a transient burst train appears on the high-speed real-time oscilloscope (DPO75902SX, 200 GS/s, 59 GHz, Tektronix). The experimentally observed waveforms in time domain with periodicity of the different pulses are clearly shown in Fig.2. These time domain signals vary over time and we captured some pulses with narrow widths as depicted in Fig.2(a), some pulses with wider width as shown in Fig.2(b) and some with multiple pulses as displayed in Fig.2(c) as well as in Fig.2(d). However, they all have the same period 10.5 μs, which matches well with the 2.2 km fiber length of the loop.



(a)



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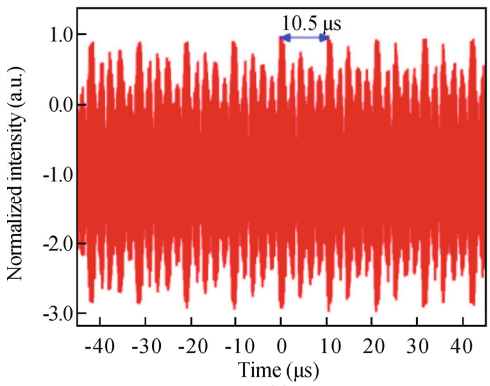
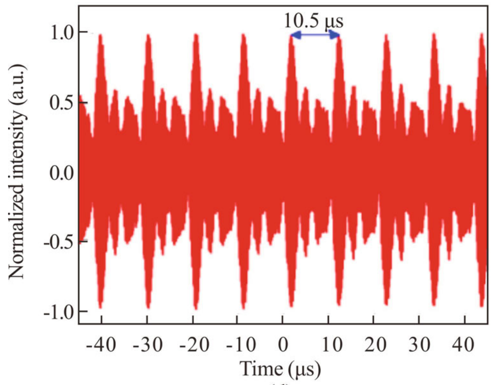


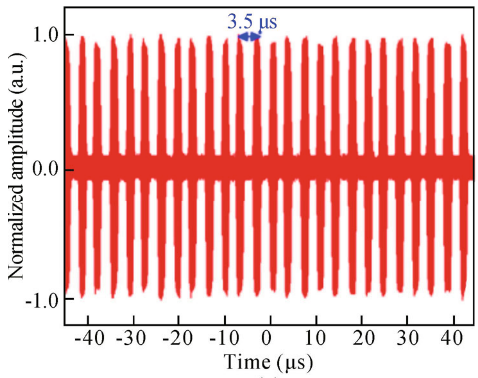
(c)



(d)

Fig.2 Experimental results of the regular pulse trains: (a) Regular time-domain pulse train with narrow pulse width; (b) Regular time-domain pulse train with wide pulse width; (c) and (d) Regular time-domain multi-pulse trains

In order to study the phenomenon of regular pulses more clearly, we carefully adjusted the optical power via the VOA while keeping an eye on the oscilloscope. This adjustment is equivalent to finely tuning the balance between the gain and cavity loss in the oscillation loop. Through constant adjustment over time, we observed a very regular pulse train as depicted in Fig.3(a). The time domain waveform is like a soliton pulse train with a time interval of 3.5 μs, which is very similar to the results of mode-locked OEO of our previous work[11,12]. Fig.3(b) presents the corresponding spectrum measured using a spectrum analyzer (FSWP50, 1 MHz—50 GHz, Rohde & Schwarz) in 200 Hz resolution bandwidth (RBW) with a center frequency of 10 GHz and a 3 dB bandwidth of 0.57 MHz. The inset indicates the mode spacing is 285 kHz, matching well with the third harmonic of the 2.2 km long fiber in the ring cavity. It should be noted that there are three-group modes oscillating simultaneously and competing with each other in the OEO. This phenomenon is similar to the supermodel noise in actively mode-locked lasers[19] and harmonically mode-locked OEO[11,20]. A single pulse is shown in Fig.3(c), and the full width at half maximum (FWHM) of the pulse is about 1.30 μs. After zooming in the single pulse in Fig.3(c), the waveform of the carrier signal with a center frequency of 10 GHz can be seen in Fig.3(d).



(a)

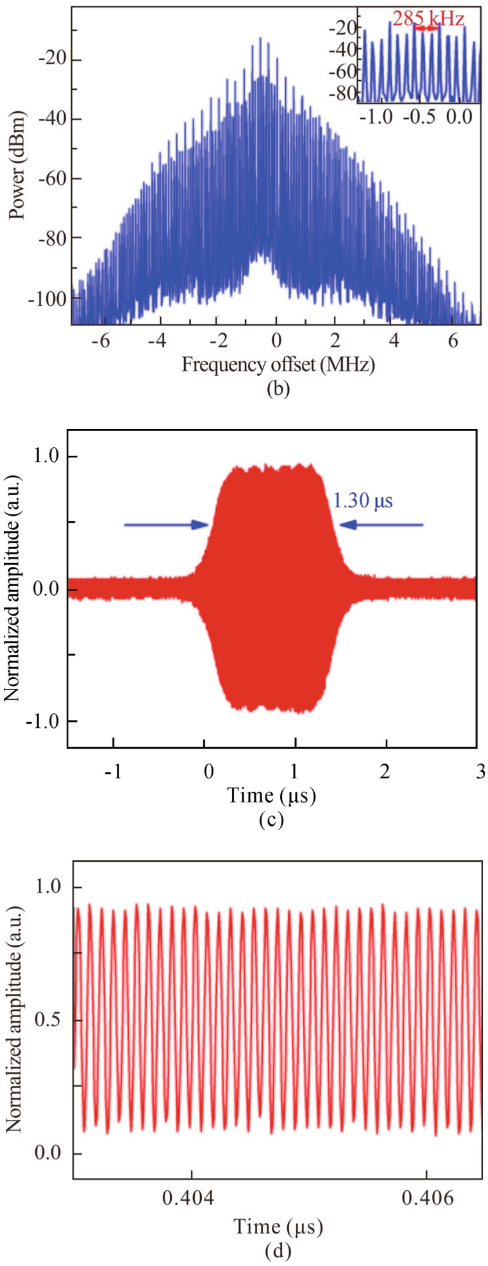
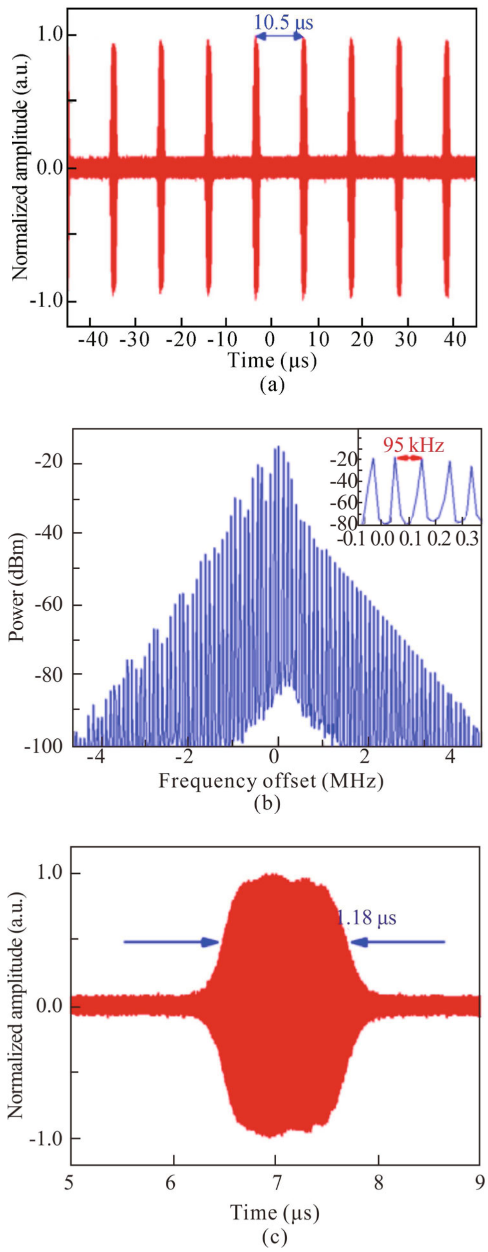


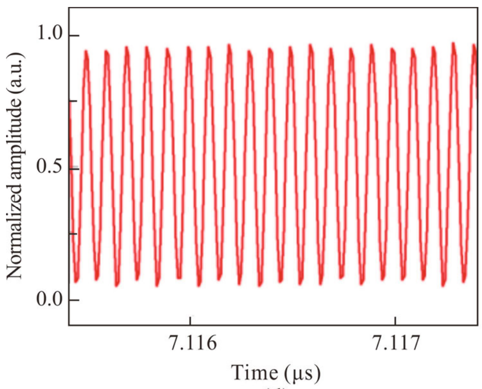
Fig.3 Experimental results of the third harmonic pulse sequence: (a) Regular time-domain pulse train (Time interval of 3.5 μs between adjacent pulses is indicated); (b) Spectrum of the pulse train in frequency domain (The inset shows the detail of the microwave frequency comb with a 285 kHz interval); (c) Envelope of a single microwave pulse; (d) Inner structure electric field of a single pulse

As the MZM bias point drifted around the maximum transmittance position, we subsequently also observed the generation of fundamental burst states.

The related experimental results are shown in Fig.4. Specifically, the fundamental pulse time domain waveforms and their spectral information are presented in Fig.4(a) and (b), respectively. As can be seen from the graph, the time interval between two adjacent pulses is 10.5 μs and the spacing of the frequency comb is 95 kHz. This means that there is only one pulse inside the resonant cavity during one round trip. The individual soliton pulse waveforms and details are also shown in Fig.4(c) and (d), respectively. Analysis shows that the FWHM of the pulse is about 1.18 μs, which is limited by the bandwidth of the filter. Further compression of the width of the soliton may be achieved by increasing the bandwidth of the loop filter. However, wider filters may cause instabilities for the solitons formation and eventually chaotic states may appear[16].

The regular pulse train observed experimentally here is similar to the mode-locked OEO pulses we have previously studied in the time domain, with the pulse width depending on the bandwidth of the filter and the pulse spacing equal to the time delay of the resonant cavity. Although the pulse trains observed here are not stable over time, they clearly indicate the possible existence of a nonlinear feature in the OEO that is similar to saturable





(d)

Fig.4 Experimental results of the fundamental frequency pulse sequence: (a) Regular time-domain solitons pulse train (Time interval of 10.5 μs between adjacent pulses is indicated); (b) Spectrum of the pulse train in frequency domain (The inset shows the detail of the microwave frequency comb with a 95 kHz interval); (c) Envelope of a single microwave pulse; (d) Inner structure electric field of a single pulse

absorption. A detailed study of the dynamical phenomena near the quadrature point has been carried out[16], revealing that the generated signal generates bifurcation as the loop gain increases, and that the formation of regular breather chaos is observed. In particular, a passive mode-locked OEO has been experimentally implemented when the bias point of the MZM is set at its lowest point[8], and it has been shown that the MZM has saturable absorption properties.

Here, we focused on the nonlinear dynamics when the bias point was at its highest point, and we similarly observed the presence of pulse formation. It is important to note that Ref.[15] has also done related studies near the maximum point of MZM, but they have mainly concentrated on the process of broadband chaotic signal generation. Although they also mention the existence of a stable pulse state in their system, they do not clearly show experimental results similar to those presented in this paper. We believe the quasi-steady-state bursts observed here may be caused by the nonlinear gain of the MZM balanced by the interaction of the BPF, and the instability may arise from the imbalance of the gain and loss or other parameters. The pulse state found here is a wave packet soliton state that is localized in the time domain and is distinctly different from the soliton states recently found in OEO with spontaneous frequency hopping[21]. Thus, we believe that the findings here will stimulate further theoretical work.

We have observed the generation of periodically regular pulse trains of microwave signals in a narrow-band OEO and suggested that the formation of pulses originates from a balance between the nonlinear gain of the MZM and the pulse broadening effect induced by the BPF. The experimentally observed quasi-steady-state pulse sequence has the wave packet characteristics of a soliton state and exhibits clear periodicity in the time domain with a period of 10.5 μs, pulse width of about 1 μs, a center frequency of 10 GHz and comb spacing of about 95 kHz in the frequency domain. The pulses are very similar in nature to those observed in mode-locked OEOs. Our results are of great importance for deepening the understanding of the nonlinear dynamical processes in OEO systems and enriching the physical processes in time-delayed dynamical systems.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

References

[1] YAO X S, MALEKI L, DAVIS L. Coupled optoelectronic oscillators for generating both RF signal and optical pulses[J]. Journal of lightwave technology, 2000, 18(1): 73-78.

[2] YAO X S, MALEKI L. Multiloop optoelectronic oscillator[J]. IEEE journal of quantum electron, 2000, 36(1): 79-84.

[3] ZHANG J J, YAO J P. Parity-time-symmetric optoelectronic oscillator[J]. Science advances, 2018, 4(6): eaar6782.

[4] FAN Z Q, QIU Q, SU J, et al. Tunable low-drift spurious-free optoelectronic oscillator based on injection locking and time delay compensation[J]. Optics letters, 2019, 44(3): 534-537.

[5] ZHANG Y L, HOU D, ZHAO J Y. Long-term frequency stabilization of an optoelectronic oscillator using phase-locked loop[J]. Journal of lightwave technology, 2014, 32(13): 2408-2414.

[6] HAO T F, LIU Y Z, TANG J, et al. Recent advances in optoelectronic oscillators[J]. Advanced photonics, 2020, 2(4): 044001.

[7] CHEMBO Y K, BRUNNER D, JACQUOT M, et al. Optoelectronic oscillators with time-delayed feedback[J]. Review of modern physics, 2019, 91(3): 035006.

[8] LEVY E C, HOROWITZ M. Single-cycle radio-frequency pulse generation by an optoelectronic oscillator[J]. Optics express, 2011, 19(18): 17599-17608.

[9] YANG B, ZHAO H Y, CAO Z Z, et al. Active mode-locking optoelectronic oscillator[J]. Optics express, 2020, 28(22): 33220.

[10] ZENG Z, ZHANG L J, ZHANG Y W, et al. Microwave pulse generation via employing an electric signal modulator to achieve time-domain mode locking in an optoelectronic oscillator[J]. Optics letters, 2021, 46(9): 2107-2110.

[11] TUO Z Y, ZHAO C B, MENG Y S, et al. Rational harmonic mode-locked optoelectronic oscillator[C]//5th Optics Young Scientist Summit, September 16-19, 2022, Fuzhou, China. Washington: SPIE, 2022: 1244807.

[12] TUO Z Y, ZHAO C B, MENG Y S, et al. Regeneratively mode-locked optoelectronic oscillator[J]. Optics express, 2022, 30(24): 43779-43786.

[13] HAO T F, CEN Q Z, DAI Y T, et al. Breaking the limitation of mode building time in an optoelectronic oscillator[J]. Nature communications, 2018, 9: 1839.

[14] YAO X S, HAO P, LU H, et al. Fourier domain mode-locked opto-electronic oscillator with a diode-tuned bandpass filter[J]. Optics express, 2020, 28(16): 23454-23466.

[15] CALLAN K E, ILLING L, GAO Z, et al. Broadband chaos generated by an opto-electronic oscillator[J]. Physical review letter, 2010, 104(11): 113901.

[16] KOUOMOU Y C, COLET P, LARGER L, et al. Chaotic breathers in delayed electro-optical systems[J]. Physical review letter, 2005, 95(20): 203903.

[17] KOUOMOU Y C, LARGER L, TAVERNIER H, et al. Dynamic instabilities of microwaves generated with optoelectronic oscillators[J]. Optics letters, 2007, 32(17): 2571-2573.

[18] HAO T F, DING H, LI W, et al. Dissipative microwave photonic solitons in spontaneous frequency-hopping optoelectronic oscillators[J]. Photonics research, 2022, 10(5): 1280-1289.

[19] POTTIEZ O, DEPARIS O, KIYAN R, et al. Supermode noise of harmonically mode-locked erbium fiber lasers with composite cavity[J]. IEEE journal of quantum electronics, 2002, 38(3): 252-259.

[20] ZENG Z, ZHANG Z, ZHANG L, et al. Harmonically mode-locked optoelectronic oscillator with ultra-low supermode noise[J]. Optics & laser technology, 2022, 151: 108036.

[21] HAO T F, DING H, LI W, et al. Dissipative microwave photonic solitons in spontaneous frequency-hopping optoelectronic oscillators[J]. Photonics research, 2022, 10(5): 1280-1289.