# Temporal Cavity Solitons With Tunable High-Repetition-Rate Generation in a Brillouin Pulse Laser Cavity

Wenhao Xiong, Chuanfei Yao, Pingxue Li, Yixuan Wang, and Feiyu Zhu

***Abstract*—In this paper, we report a new method to generate tunable high-repetition-rate temporal cavity solitons (TCSs) in a nonlinear fiber cavity, which is driven by dual Brillouin laser pulses. This method is more feasible than generating solitons via a continuous optical-driven nonlinear cavity because of the enhanced four-wave mixing process triggered by the high peak intensity Brillouin laser pulses. The generated TCSs lock to the beating signal arriving from dual Brillouin pulses, which allows the repetition rate of the solitons to be directly tuned all- optically. The TCSs can be continuously tuned over a repetition rate range of 140∼242 GHz by controlling the external dual-wavelength spacing, and the pulse duration can be accordingly adjusted from 0.9 ps to 513 fs. Such TCSs with tunable high-repetition-rate can provide a practical solution for the low-noise controllable millimeter-wave and terahertz sources.**

***Index Terms*—Dual pulse Brillouin laser, Kerr frequency comb, temporal cavity solitons, tuning mode spacing.**

## I. Introduction

THE ability of temporal dissipative Kerr–cavity solitons (DKSs) to generate broadband-coherent combs with gigahertz repetition rates and short pulse streams has a number of applications [1], such as parallel coherent laser ranging [2], coherent communication systems [3], photonic microwave [4], etc. Generally, the external pumped laser drives the Kerr nonlinear cavity to produce cavity solitons through modulation instability (MI) [5] and cascaded four-wave mixing (FWM) [6], [7]. Meanwhile, the excellent dispersion flattening and high nonlinear coefficient of optical media are also indispensable. DKSs were first demonstrated in a fiber cavity by optical comb formation, which showed un-tunable solitons superimposed on a continuous wave (C.W.) background [8]. Likewise, such phase-locked DKSs have been generated in a wide variety of micro-resonators [1], [9], especially the structure of the rings, disks, and spheres based on different platforms. Both fiber cavity and micro-resonators enable produce DKSs with the fixed repetition rate ranging from gigahertz to terahertz [10], [11], while the free spectral range (FSR) determined by the optical cavity limits its tunability. Indeed, the frequency lines of the DKSs are strictly zero-detuning matched at the resonant peak of the optical cavity. The repetition rate of DKSs is not tunable in these resonators as it is fixed by the resonator's Opto-geometrical parameters. Therefore, to further expand the application range, the current generation of temporal cavity solitons (TCSs) with tunable high-repetition-rate is still worth exploring.

An effective approach to obtain the Kerr combs with large tunable frequency separation is to exploit the cascaded FWM process in a dual-wavelength-pumped optical nonlinear cavity [12]–[14]. Dual pumping (or bichromatic pumping) not only provides greater control and flexibility for the formation of optical comb, but also supports the rich dynamics of TCSs. Hansson *et al.* broke through the conventional single-pump scheme, and numerical simulations were made to demonstrate dual-pumping driven for the generation of microcavity solitons [12]. This pulse train has no fundamental mode spacing but rather the mode spacing of the pump, i.e., multiples of the FSR. Recently, Li *et al.* demonstrated the cavity-enhanced cascaded FWM OFCs in a dual Brillouin laser fiber cavity, which mode tooth linewidth inherited the narrow linewidth of Brillouin laser [14]. The generation of OFCs with a step tunable mode spacing from 40 to 1300 GHz by controlling the external wavelength spacing got rid of the constraint of cavity FSR. However, obtaining high parametric gain conversion in the cavity is still difficult due to the low figure of merit (FoM) of the cavity caused by the low-power C.W. [15]. Moreover, the reduction in peak power of the intracavity pulses with increasing comb spacing will further weaken the parametric efficiency.

The formation of TCSs always relies on a double balance of dispersion and nonlinearity as well as (parametric) gain and cavity loss. The comb lines are generated by means of cascaded FWM process and undergo a self-organization process that leads to the emergence of a soliton pulse train [1]. In fact, the losses in a passive nonlinear optical cavity are compensated by a parametric interaction. Recently, benefiting from the distinguished advantages such as high peak power and tunability, modulated pulses have been regarded as promising means of pumping in the parametric process [16], [17]. Generally, the high parametric gain is to reach high-quality phase-locked pulse emission. Luo *et al.* employed quasi C.W. two pumps and generated tunable

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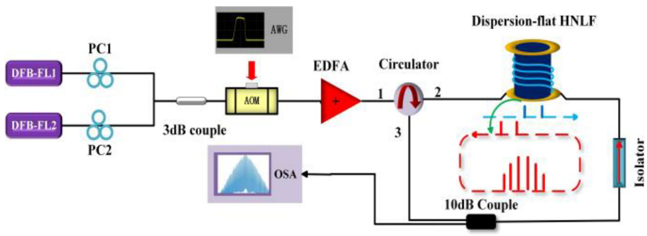


Fig. 1. Schematic diagram of the experimental setup: DFB-FL1&DFB-FL2, distributed feedback fiber laser; PC1&PC2, polarization controller; AOM, acousto-optic intensity modulator; AWG, arbitrary waveform generator; EDFA, erbium-doped fiber amplifier; optical circulator; HNLF, highly nonlinear fiber; OSA, optical spectrum analyzer.

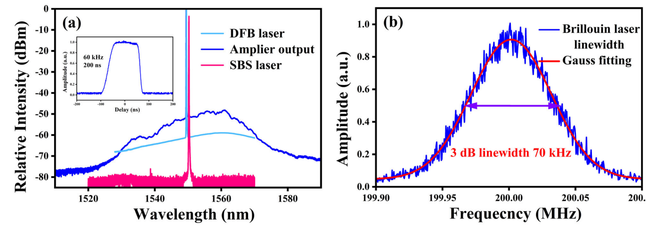


Fig. 2. (a) Optical spectrum of SBS laser, amplifier and DFB lasers captured by OSA at 0.02 nm RBW. Inset shows the corresponding square pulse profile of Brillouin laser. (b) The delayed self-heterodyne beating radio frequency spectra of the Brillouin laser.

high-repetition-rate (0.1–1THz) femtosecond pulses in highly-nonlinear fiber (HNLF) [17]. Such a non-cavity setup is short of the substantial spectral filtering. The bottom of the comb lines is not clear and chaotic caused by the amplified spontaneous emission (ASE) noise of the amplifier.

In this paper, we demonstrated a new method to generate tunable high-repetition-rate TCSs, which was realized by seeding the two pulses pumped passive ring cavity made of dispersion-flat HNLF. The two narrow linewidth Brillouin nanosecond pulses were used as the direct pump for the effective formation of TCSs. Neither the dual-pumping frequency nor the cavity resonance was required to be tuned. As the result, the repetition rate of TCSs could be tuned continuously in the range of 140∼242 GHz and the pulse duration could be correspondingly adjusted from 0.9 ps to 513 fs.

## II. Experimental Setup

The generating device of soliton comb formation based on dual-pulse Brillouin laser intra-cavity pumping is depicted in Fig. 1. Two C.W. single-frequency distributed feedback fiber laser (DFB-FL1&DFB-FL2) at the C band with a frequency separation $f$ (line widths ∼10 kHz) were first combined by a 3-dB optical coupler (OC), and modulated by an acousto-optic intensity modulator (AOM) with a 60-kHz repetition rate. The two pulses modulated were then amplified to 75 mW with a two-stage home-made erbium-doped fiber amplifier (EDFA) and used as the pump source for achieving dual-wavelength Brillouin pulsed laser. The amplified dual pulses were early set to 180 ns long square pulses at 60 kHz repetition rate by arbitrary waveform generator (AWG), thus obtaining the peak power of ∼3.5 W. Immediately, the generated pulsed pump beam was launched into the ring cavity by port 1 of an optical circulator. An all-fiber dual-wavelength pulsed Brillouin ring cavity laser was constructed by connecting ports 2 and 3 of the optical circulator through a 200 m dispersion-flat HNLF, an optical isolator, and a 10 dB OC. The HNLF used in our experiments (NL-1550-zero, YOFC Inc) had the nonlinear coefficient of 10 $W^{-1}km^{-1}$, attenuation below 1.5 dB/km, the low dispersion area ($-1.1 \rightarrow +1.1$ ps/nm/km) from 1500 to 1600 nm, a dispersion coefficient of 0.389 ps/nm/km and a dispersion slope of 0.017 ps/nm$^2$/km@1550 nm. TCSs were output from one terminal (10%) of the 10 dB OC. The output signal was analyzed by using an optical spectrum analyzer (OSA, AQ6370D), a commercial frequency-resolved optical gating (FROG), and a power meter respectively.

## III. Experimental Results And Analysis

To further investigate the performance of the optical nonlinear cavity, one of the two DFB fiber lasers was first turned on. When the total pump power out of ring cavity $P_{total}$ was gradually increased to 35 mW, we observed the one strong stimulated Brillouin scattering (SBS) laser with a wavelength redshift of 0.8 nm at the output of the ring cavity. By introducing the optical circulator and the optical isolator into the laser cavity, the pump laser performs only a single turn, and there is no resonant condition for the pump laser [18]. Fig. 2(a) shows the measured output spectra of the DFB laser, home-made EDFA and ring cavity. Thanks to the spectral width of Brillouin gain of intracavity excitation as narrow as a few tens of megahertz [19], the optical signal to noise ratio (OSNR) of Brillouin laser was as high as 70 dB after filtering ASE noise automatically.

Moreover, the cavity feedback is responsible for phase noise and relative intensity noise (RIN) suppression of the pump laser, thereby yielding a narrower spectral linewidth and highly coherent Brillouin laser in a nonlinear ring cavity [20]. It's noted that it is still about 10 dB higher than the OSNR of the original DFB laser. Besides, the insert shows the corresponding square pulse profile. Fig. 2(b) shows the delayed self-heterodyne beating radio frequency spectra of the fundamental order SBS laser. For ultra-narrow linewidth fiber laser, due to the large 1 / f frequency noise, the Gaussian function was used to fit its line shape [21]. The measured full-width at half-maximum (FWHM) is 70 kHz and the corresponding linewidth is 49.5 kHz. Strikingly, it is the narrower linewidth and higher peak power that makes the pulsed Brillouin laser an excellent pump light for the Kerr comb formation.

In the following experiment, we investigated the generation of TCSs with the large tunable repetition rate in all-fiber cavity and observed different time-domain behaviors. In the passive nonlinear optical cavity, the Kerr nonlinear process triggered by the external pump light compensates for the resonant cavity losses, which is the basis for the formation of TCSs. The wavelength spacing between the two DFB fiber lasers was specifically set to be 1.94 nm (separated by 242 GHz). The frequency interval of

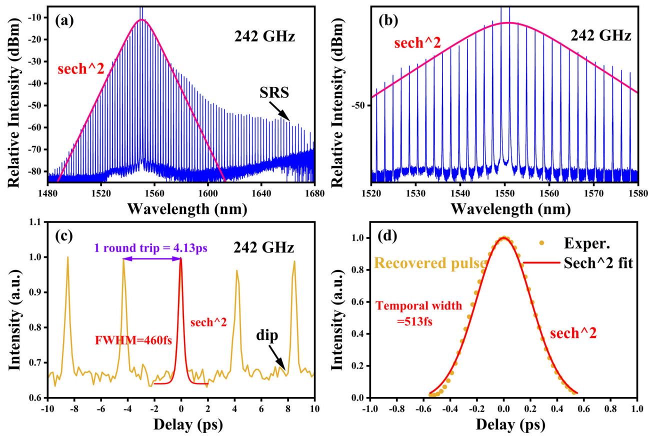


Fig. 3. Output characteristics of the frequency combs in frequency separation of 242 GHz when the pump power is 75mW. (a) Optical spectrum. (b) C-band spectrum of the comb. (c) Typical autocorrelation traces. (d) Single pulse recovered from the autocorrelation trace.

the dual-pumping laser is an integral multiple of the FSR of the ring cavity, which means that the intracavity dual Brillouin lasers are located in the resonant region of the fiber cavity. It should be noted that solitons will be generated spontaneously when the laser frequency in the cavity resonates with the cavity. The initial dual modulated-pulse pump lasers were amplified to 75 mW and launched into the mentioned Brillouin ring cavity. The average output power of the cavity was 4.2 mW. Significantly, the peak power of the pump pulse is as high as 3.5 W. As the pump power increased, it was observed that the comb lines formed as a cascade of sideband spaced by approximately one f, which spread from the dual pumping lines.

Fig. 3 further summarizes the output characteristics of the TCSs in Brillouin cavity based on cascaded-FWM. As can be seen in Fig. 3(a), the comb lines cover more than 100 nm and have a very low signal noise base because it inherits the time-frequency characteristics of the Brillouin laser. Generated comb spectrum was characterized by a smooth spectral envelope, without spectral gaps. The dual pump lines were usually part of the comb spectrum in our experiments, which were typically 8-10 dB stronger than the adjacent comb lines. Fig. 3(b) shows the C-band spectrum with 87 comb lines. The envelope of the comb lines spread out from both sides of the dual pump lasers has a hyperbolic secant shape with a 3-dB bandwidth of 7.2 nm. It is well known that the cascaded-FWM process would occur efficiently as the pump peak power and OSNR level is high enough [22]. The top of the combs profile transitions from sharp to smooth and full, except for the pump lines, because of the high parameter conversion efficiency, which substantially improves time-domain pulse quality.

Although SBS by itself would not lead to phase-locking of comb frequency components, FWM is sensitive to the spectral phase, and the contribution of FWM can lead to equally spaced, phase-locked OFCs with deterministic spectral phases. In fact, soliton pulses formed spontaneously without the need for external stimulation in the fiber cavity. It is worth noting that the intensity of the entire spectral lines decreases from the center to edges significantly, which is the typical characteristic of the dissipative FWM mode-locking [23]. The part of the comb lines near the two pumps has a hyperbolic secant profile, which begins to have the characteristics of TCSs.

To better analyze the operation of cavity soliton states, their temporal properties have been investigated by FROG. Fig. 3(c) illustrates the corresponding autocorrelation trace. The one round trip of the pulse train is 4.13 ps, demonstrating that the laser delivers a pulse train of 242 GHz repetition rate. The newly formed ultra-short pulses propagated without distortion in the cavity, highlighting the soliton characteristics of the intracavity pulses. The temporal field envelope exhibited a $sech^2$ shape, which has a FWHM of 460 fs. The dip of C.W. background on both sides of the pulse is a representative feature of TCSs, which is particularly well reproduced [8]. TCSs carried intense peak power and ultrashort duration, and induced stimulated Raman scattering (SRS) effect which started to shift the pulse spectrum to the redshift region, shown in Fig. 3(a). In this case, the field in the cavity is periodically uniform in one region and modulated in another region. Due to the dissipative FWM mechanism in the Brillouin ring cavity, the power conversion efficiency is still lower than 5%, although the peak power is increased by using the pulsed pump. The independent phase of the rest pump light also leads to the higher base noise of the autocorrelation signal [23]. Fig. 3(d) shows the time domain field envelope recovered from the autocorrelation trace. The pulse profiles have the $sech^2$-shape characteristic and its FWHM is 513 fs. The intracavity pulses transit from the initial sine waves to the mode-locked femtosecond pulses, which show good coherence properties [24]. These results indicate that we have successfully realized TCSs inside our cavity.

The TCSs generated by the dual-pulse Brillouin laser pumped also possess a wide range of tunable properties. It's still difficult to obtain tunable period microcavity solitons in previous studies. For TCSs generation via intra-cavity pulsed pumping, the solitons lock to the driving optical sine wave created by two beating Brillouin laser tones. The frequency interval of the dual Brillouin lasers had been always consistent with that of the dual DFB single-frequency fiber lasers. Neither the pump frequency nor the cavity resonance was required to be tuned. By setting the wavelength interval between the two lasers outside the cavity, we can directly control the repetition rate of the TCSs, which also means that the comb tooth interval can be tuned in a wide range. As shown in Fig. 4(a1)–(a5), we representatively summarize the output spectra of the TCSs at the repetition rates of 140162, 183200, and 225 GHz, respectively. The optical spectrum all have a typical parabolic shape. The correspondingly measured pulse widths are 0.89, 0.81, 0.715, 0.63 and 0.52 ps, shown in Fig. 4(b1)–(b5). The generated soliton pulses have stable temporal output characteristics. It could be very promising that the period and the pulse duration can be flexibly tuned over a large range, which further expands the application range of TCSs with the large tunability.

Finally, we also tested frequency combs with smaller comb spacing. At this point, the gain of modulation instability brought additional phase noise, causing chaos at the bottom of the comb teeth. The cavity soliton frequency comb with small comb

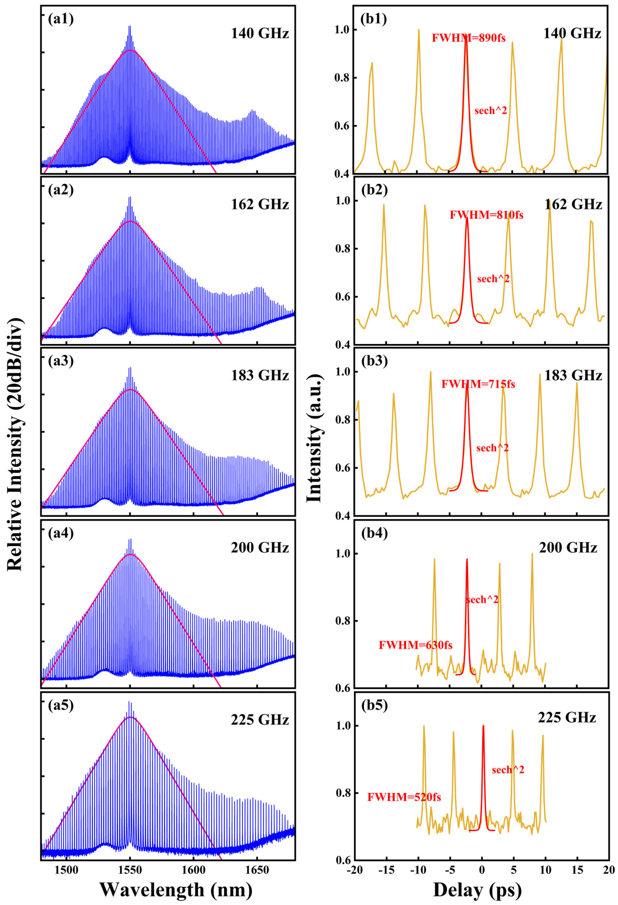


Fig. 4. Output temporal cavity soliton spectrum in frequency separation of (a1), (b1) 140 GHz; (a2), (b2) 162 GHz; (a3), (b3) 183 GHz; (a4), (b4) 200 GHz; (a5), (b5) 225 GHz for a cavity length of 200 m. The red curves indicate the $sech^2$ fitting for the envelope of the spectrum profile.

spacing still needs to be further improved in the future. In addition, TCSs with higher tunable repetition rate cannot be obtained, which is mainly limited by the narrow wavelength tuning range of the current external single-frequency distributed fiber laser.

## IV. Conclusion

In conclusion, we have proposed a pulsed dual-Brillouin laser pumped nonlinear fiber cavity scheme to successfully present TCSs with a large range tunable repetition rate. In contrast to previous microcavity-based work, the generation of solitons was enabled by two external pumps, which made it flexible and tunable. Pulsed driving means a higher parametric gain in comparison to a C. W. -Driven system, which realizes high-quality femtosecond soliton pulses. This method provides a more efficient approach for the generation of TCSs in the future, which would be used for the low-noise controllable millimeter-wave and terahertz sources.

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