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# Characterizing and Modeling Kerr Frequency Combs in Fiber Cavity Brillouin Lasers

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**Abstract:** We study a re-configurable nonreciprocal ring cavity setup to generate tunable optical frequency combs. Coherent combs can be obtained by finely exploiting stimulated Brillouin scattering and cascaded four-wave mixing in the nonlinear fiber cavity. © 2022 The Author(s)

Optical frequency combs (OFCs), whose broadband spectrum consists of discrete, equi-spaced frequency lines, are a very powerful tool in a wide range of applications such as optical frequency metrology, spectroscopy, astronomical spectrograph calibration, wavelength division multiplexing, and microwaves generation [1, 2]. Different optical technologies can be used to generate such OFCs, such as mode-locked lasers, electro-optical modulation, and nonlinear frequency conversion in passive optical resonators [1, 3]. In this contribution, we study a re-configurable system based on a bi-chromatic Brillouin fiber laser [4], to generate a Kerr comb. We present numerical and experimental studies of the nonlinear cavity, highlighting the potential, robustness and limitations of such hybrid systems that take advantage of stimulated Brillouin scattering and multiple four-wave mixing processes.

Figure 1a presents the experimental setup, which is based on a nonlinear fiber cavity closed by an optical circulator, a typical configuration for Brillouin lasers [5]. The operating principle of the hybrid system is illustrated in Fig. 1b. Thanks to the circulator, the two pump lasers can circulate freely in the clockwise direction and are not subject to a resonance condition. They generate Brillouin Stokes waves in the opposite direction, which resonate and build up to form laser lines, which produce in turn a four-wave mixing (FWM) cascade. The bi-chromatic pumping configuration can be achieved by combining two continuous lasers or, as shown in Fig. 1a, by means of electro-optical modulation, to easily change the frequency spacing of the comb, here fixed to 40 GHz (much higher than the free spectral range of the cavity).

Several commercially available highly nonlinear fibers (HNLF) were tested to form the cavity, thus allowing the impact of net cavity dispersion to be studied. Two typical examples of Kerr combs obtained in the normal and anomalous dispersion regimes are shown in Figs. 1d,e, respectively. Though not apparent in Fig. 1e, we noted the growth of spontaneous modulation instability bands on the comb spectrum at higher power in the anomalous dispersion regime. Different cavity lengths were also used to verify the impact of multimode Brillouin lasing on the comb. Indeed, despite the narrow width of the Brillouin gain (typ. 50 MHz), for smaller free spectral range (FSR) of the cavity, several modes can oscillate simultaneously, especially at high power. This feature of each Brillouin laser line is monitored by measuring the beat with its pump laser. Our observations show that cavities exceeding  $\sim 80$  m oscillate in multiple longitudinal modes before the spectral comb emergence through FWM, which strongly degrades the comb coherence, reduces the power per line, and increases the noise floor. Other limiting factors, such as mode hopping, are mitigated via various stabilization schemes, such as phase locking the pump-Stokes beatnote [5] or using the Pound-Drever-Hall (PDH) technique.

In addition, we developed a specific model to simulate the generation of frequency combs in this type of laser cavity, which is based on a set of three coupled equations derived from the Ikeda map. The first one is a nonlinear Schrödinger equation (integration by split-step Fourier method) to describe the nonlinear propagation of Stokes waves in the cavity fibers, the second accounts for their recirculation and resonance conditions, and the third equation determines the steady-state Brillouin gain before each roundtrip, as a function of the intracavity Stokes power and the input pump power. The cavity losses are first estimated in open loop. This value, as well as the Brillouin gain value, are then adjusted to match the Brillouin laser threshold measurement with a single pump (see Fig. 1c). Despite the absence of a resonance condition for the pump lasers, when the system operates in the highly coherent regime, our simulation-experiment comparisons highlight the importance of taking into account the residual detuning between the gain peak and the lasing mode, as observed in microresonators [6, 7, 8]. Moreover, the mismatch between the frequency spacing and the FSR-multiple of the cavity also has a significant impact on the spectral width and symmetry of the comb.

Our numerical predictions match the experimental data remarkably well. In the case of a normal net dispersion (Fig. 1d), the comb is formed by the formation of a switching wave onto the sinusoidal modulation pattern resulting from the interference between the two Stokes fields in the cavity. In the case of anomalous net dispersion

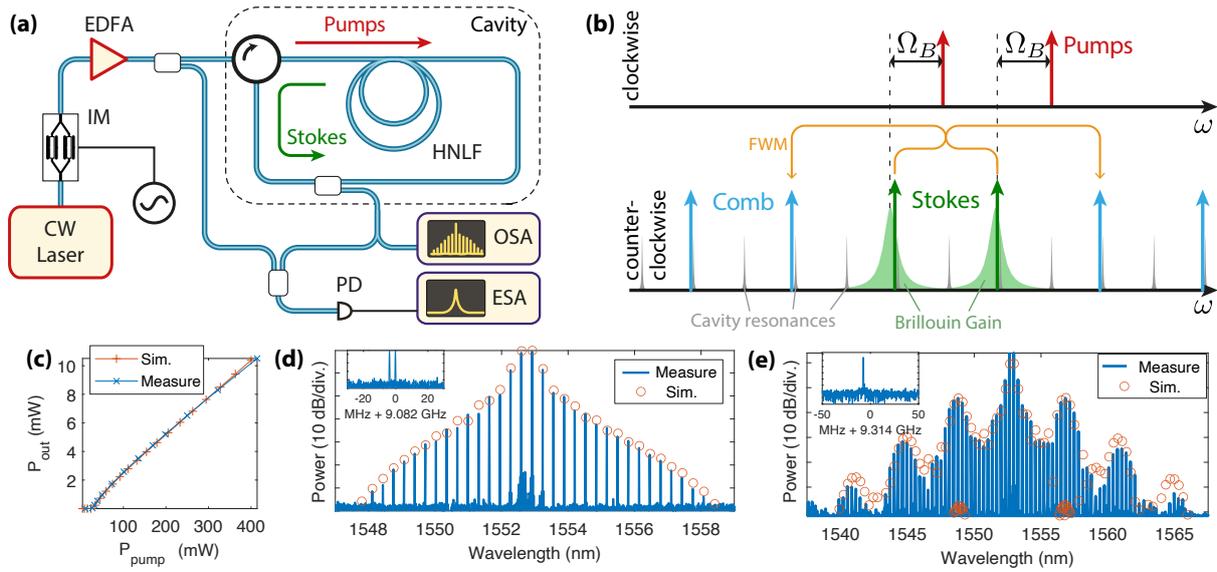


Fig. 1. **(a)** Experimental setup for Kerr comb generation in a Brillouin fiber laser. IM: intensity modulator; HNLF: highly nonlinear fiber; OSA: optical spectrum analyzer; PD: photodiode; ESA: electrical spectrum analyzer. **(b)** Principle of Kerr comb formation in a Brillouin laser cavity. The pumps circulating in the clockwise direction are not resonant because of the circulator. They induce Brillouin-Stokes gain bands shifted by the elastic phonon frequency  $\Omega_B$ , which cause a lasing effect on the cavity resonance modes. These two Brillouin lasers then initiate a four-wave mixing (FWM) cascade, leading to the formation of a comb whose line separation is controlled by the pump spacing. **(c)** Threshold measurement of the Brillouin laser with a single pump (15 m-long cavity) **(d)** Frequency comb obtained in the normal dispersion regime (15 m cavity,  $P_{\text{pump}} = 230$  mW). The beat-notes between the Stokes lasers and their pumps (centered around  $\Omega_B/2\pi$ ) are shown in the inset. They show excellent coherence under these conditions (100 kHz resolution bandwidth). **(e)** Same measurements performed in the anomalous dispersion regime (60 m cavity,  $P_{\text{pump}} = 180$  mW). The beat of a single laser is shown in the inset.

(Fig. 1e), the comb results from the formation of localized structures (by modulation instability) on each peak of the sinusoidal modulation. The slight shift in the position of the comb lobes between the measurement and the simulation is likely due to a slight miscalculation of the fiber dispersion. Note that when the Brillouin laser becomes multimode (by increasing the pumping power, or the length of the cavity), the simulation-experiment agreement progressively deteriorates due to the random behavior of the laser.

In conclusion, our first results confirm an interesting alternative to other frequency comb generation methods. They also shed new light on the first studies of these hybrid systems, notably concerning the coherence of the comb [4, 9]. A step of optimization of the cavity design is in progress to maximize the spectral width of the comb while preserving its coherence. Finally, we are working on replicating these results further into the mid-infrared, which is more appropriate for spectroscopy.

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