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Optical Waveform Sculpturing of a Frequency Kerr Comb from a Brillouin Laser Cavity with Bichromatic Pumping

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ABSTRACT

We numerically and experimentally investigate the spectral phase profile of a frequency comb generated by the Kerr effect in a Brillouin fiber laser, architecture of which comprises bichromatic pumping and normal dispersion fiber. By manipulating the spectral properties and exploiting the stability of the comb, we demonstrate the generation of a wide range of temporal intensity profiles at a repetition rate of 40 GHz.

Keywords: Kerr frequency combs, optical spectral shaping, Brillouin cavity.

1. INTRODUCTION

Generating a large variety of temporal waveforms such a Gaussian, parabolic, triangular or flat-top intensity profiles at repetition rates of several tens of GHz can be of crucial interest for different fields such as microwave photonics or ultrafast all-optical processing. If many approaches using phase and intensity modulators have proven to be efficient in the GHz repetition rate [1], reaching higher rates is challenging. Coherent optical Fourier synthesis has been shown to be successful [2] but its complexity remains quite high. A game changer seems to be the advent of frequency combs that have been stimulating for the past two decades, an undeniable interest thanks to their multiple applications, ranging from metrology to high-speed transmissions. Their very high coherence makes it possible to adjust the phase and spectral intensity line by line, resulting in a reshaping of the periodic time profile of intensity. Such shaping could be effectively employed on combs generated in micro-resonators [3], by the use of electro-optical elements [4] or by four-wave mixing in an optical fiber [5].

In this paper, we aim to take advantage of an alternative Kerr comb configuration generated in a Brillouin laser cavity subjected to bichromatic pumping [6, 7]. To achieve a successful spectral shaping, it is essential to know the phase profile of the frequency comb, which leads us to develop a numerical model of our system. We verify our numerical predictions experimentally and demonstrate the generation of a series of high-quality intensity and stability temporal profiles at repetition rates of 40 GHz.

2. EXPERIMENTAL SETUP

The experimental set-up implemented is schematized in Figure 1 and detailed in refs. [4, 5]. A highly nonlinear fiber (HNLF) with normal dispersion is placed in a unidirectional cavity and is pumped by two coherent spectral lines separated by 40 GHz. This results in the generation of two counterpropagative Stokes lines through the Brillouin effect, which stimulate the generation of a frequency comb by cascaded four-wave mixing. A feedback loop is used to stabilize the pump lasers on the cavity. The width of the comb and its symmetry can be controlled by fine-tuning the spectral spacing between the two pumps and their center frequency. At the output of the cavity, a quasi-symmetrical comb is recorded by a high-resolution optical spectrum analyzer (Apex OSA-APX). It is manipulated by an intensity and phase spectral shaping device (Coherent WaveShaper device) and the resulting time profile is recorded on an optically sampled oscilloscope (Exfo PSO-100) with a resolution of the picosecond range.

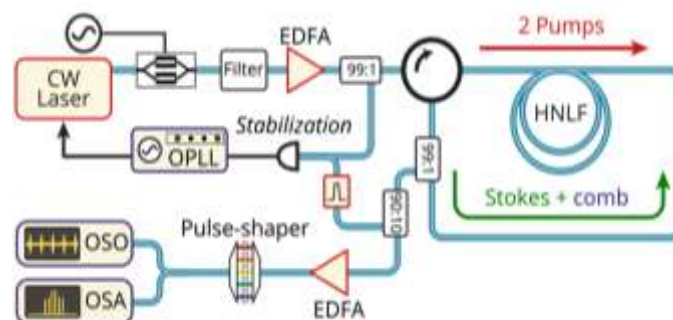


Figure 1. Experimental setup. CW : Continuous Wave ; EDFA : Erbium Doped Fiber Amplifier ; HNLF : Highly NonLinear Fiber ; OPLL : Optical Phase Locking Loop ; OSO : Optical Sampling Oscilloscope ; OSA : high resolution Optical Spectrum Analyzer

3. RESULTING FREQUENCY COMB

The experimentally measured frequency comb is shown in Figure 2(a) and highlights a good level of symmetry and a high level of optical signal to noise ratio. We compare these results with the numerical model of our cavity that is based on a system of coupled equations linking the Brillouin process and Kerr dynamics governed by the nonlinear Schrödinger equation with recirculation conditions [4, 5]. The results obtained reproduce remarkably well the experimentally measured comb over a very large span, as well as the corresponding temporal intensity profile (not shown here).

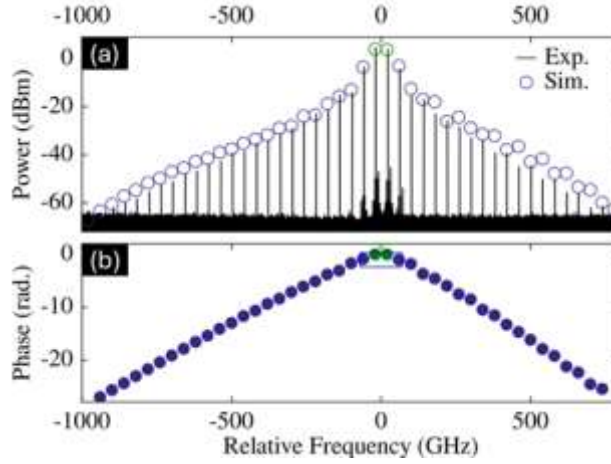


Figure 2. (a) Optical spectrum of the Kerr comb : experimental results (lines) are compared with numerical simulations (circles). (b) Optical phase extracted from numerical simulations.

These simulations allow us to confidently deduce the structure of the spectral phase profile (Figure 2, panel b). Unlike the phase profile typically observed in monochromatic pumped resonators, in our case, the phase accumulates linearly (typically -1 rad between two consecutive lines) and symmetrically on either side of the Brillouin pumps. Such relatively simple spectral phase profile allows efficient pulse compression and shaping with the simplest imprinted phase mask. We were able to corroborate these numerical predictions with experimental recordings where we isolated the central spectral components of the cavity output and altered their relative phases.

4. EXPERIMENTAL SHAPING

As a proof of concept of our ability to efficiently shape this comb, we focused on the manipulation of the four most central spectral lines where we have adjusted the amplitude ratio A and the phase difference ϕ between the two main lines and the lateral lines. Under these conditions, it was shown that the resulting RF spectrum consisting of only four components leads to a time profile of intensity corresponding to [4] :

$$I(t) = 2 \left(1 + A^2 + \cos(\omega_0 t) [1 + 2A \cos \phi] + 2A \cos \phi \cos(2\omega_0 t) + A^2 \cos(3\omega_0 t) \right) \quad (1)$$

with $\omega_0 = 2\pi R$ where R is the repetition rate of the train imposed by the spacing of the components of the bichromatic pumping scheme. According to the values of A and ϕ , various temporal profiles can be synthesized. Optimized dark parabolic, flat-top, parabolic or triangular waveforms are generated at (A, ϕ) of $(0.23, 0.7)$, $(0.23, 2.24)$, $(0.24, 1.95)$ and $(0.30, 1.55)$, respectively.

By applying the appropriate attenuation level as well as a relevant phase mask (that also pre-compensates the 1 rad phase offset stressed in the previous section), we demonstrate the wide range of temporal intensity profiles that can be accessed by our approach. Triangular, parabolic and super-Gaussian profiles are thus generated at a rate of 40 GHz. As also shown in Figure 3, the high stability observed in persistence mode confirms the high consistency of our comb.

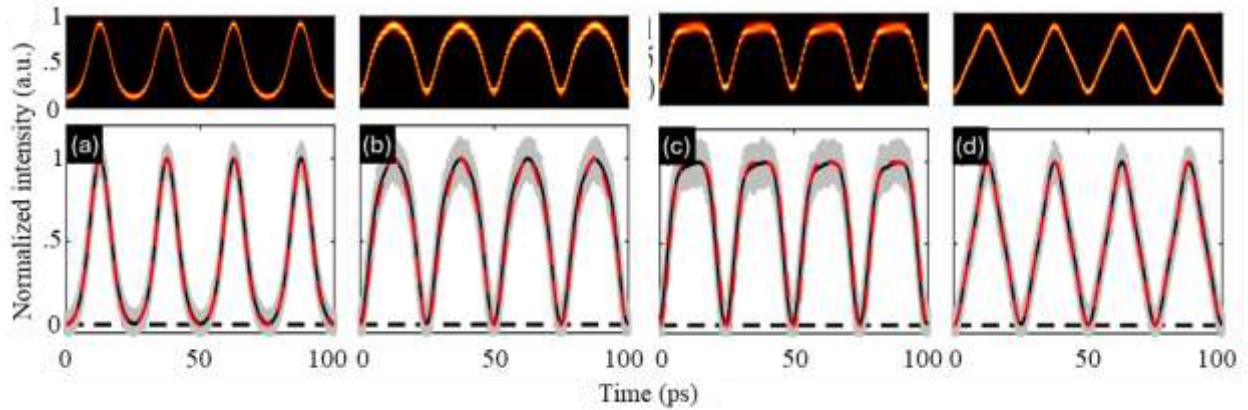


Figure 3. Experimental temporal intensity profiles obtained by spectral shaping of the four main lines of the frequency comb: dark parabolic, bright parabolic, super-Gaussian, triangular (resp. a, b, c and d). Records obtained in persistence mode (top) are compared to the averaged profiles (bottom, black curve) as well as the analytical form (red dashes). Black dashed lines highlights the zero-intensity level.

5. CONCLUSIONS

In summary, we used a pulse-shaping method to measure the relative phase between the teeth of a dual-pumped Kerr comb. Our experimental results confirm the symmetric phase relationship between the pump Stokes and adjacent lines, in agreement with numerical simulations. Our study provides insight into the dual-pumped Kerr comb dynamics and showcases the generation of diverse waveforms which, combined with the reliable low-noise spectral profile, can be used in many practical applications. Our findings suggest potential advantages in dual-pumped Kerr combs, emphasizing the absence of abrupt phase differences observed in single continuous-wave pumping. This linear and symmetric phase profile of the cavity output simplifies a phase compensation which is essential to obtain maximally compressed pulses and various waveforms. Research into advanced phase control techniques, such as an iterative optimization loop, would complement our setup towards an ultimate all-arbitrary waveform generator. This would allow for a comprehensive evaluation of the phase characteristics over a wider spectral range.

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