2718 Vol. 42, No. 14 / July 15 2017 / Optics Letters Letter

Optics Letters

Optical frequency comb generation with ultra-narrow spectral lines

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Received 26 April 2017; revised 7 June 2017; accepted 12 June 2017; posted 14 June 2017 (Doc. ID 292944); published 7 July 2017

We demonstrate an optical comb source that generates 550 ultra-narrow spectral lines with a spectral linewidth of 1.5–3 kHz, spanning over the C-band. The source originates from a single-mode Brillouin laser processed with phase modulation, pulse compression, and four-wave mixing. As a result, the narrow linewidth of the Brillouin laser improves the phase noise of every spectral line of the frequency comb.

OCIS codes: (060.2310) Fiber optics; (060.4370) Nonlinear optics, fibers; (060.3510) Lasers, fiber.

https://doi.org/10.1364/OL.42.002718

Optical frequency combs (OFCs), made of mutually phase matched and equally spaced spectral lines, are creating novel applications for spectroscopy, sensing, microwave synthesis, optical waveform generation, and physical sciences [1,2]. Of particular interest for coherent optical communication systems, OFCs play an important role when locked on a single phase reference [3]. In this context, it is desirable that the phase noise, and the associated spectral width, of the in-phase spectral lines is kept to a minimum to ensure minimizing the bit error ratio of channels corrected by digital signal backpropagation [4].

Mode-locked lasers (MLL) have traditionally been used to generate wideband OFCs from nonlinear mixing processes. This approach unfortunately leads to limited frequency pitch (i.e., frequency separation of the comb lines) tunability caused by stabilization constraints of the MLL cavity. Moreover, mode-pulling effects and chromatic dispersion in the cavity distort the frequency pitch uniformity of such combs. It turns out that for most applications, the frequency pitch tunability and uniformity are an asset. To overcome this, a cavity-free configuration driven from a low power continuous-wave (CW) pump has been proposed by Ataie *et al.* [5]. This approach enables a variation of the frequency pitch, only limited by the frequency range of a phase modulator. Other reported works with a similar electro-optic comb generation technique make use of a multiple number of modulators and dispersion engineered highly nonlinear fiber (HNLF) to produce wideband combs. In addition, no special emphasis has been given to reduce the linewidth of the seed laser.

In this Letter, we exhibit the operation of an OFC source with ultra-narrow and in-phase spectral lines in a cavity-free configuration. To ensure the generation of an OFC with narrow spectral lines, the first element of the optical processing chain is a single longitudinal mode Brillouin fiber laser (BFL) that conveys low phase noise to the OFC. Compression and mixing stages are cascaded to convert the Brillouin laser output into a full-fledged wideband OFC. The design of the source is also simplified with respect to previously reported ones as it makes use of off-the-shelf commercial HNLFs.

Figure 1 presents a schematic of the proposed OFC source. The OFC comprises two signal-processing stages in cascade, which are a BFL and a parametric comb generation stage. The BFL is pumped with a primary source (PS) that consists of an external-cavity laser (ECL) followed by an erbium-doped fiber amplifier (EDFA) with a noise figure of 4 dB. The ECL is an 8160 × series Keysight tunable laser with an optical signal-to-noise ratio (OSNR) of 60 dB and relative intensity noise of −150 dB/Hz up to 6 GHz. The PS generates Brillouin gain in the HNLF 1 enclosed in a ring cavity. Table 1 presents the specification of HNLFs used in the experiment. The slow dynamics of Brillouin scattering ensures that the linewidth of the BFL becomes significantly narrower than that of the PS [6].

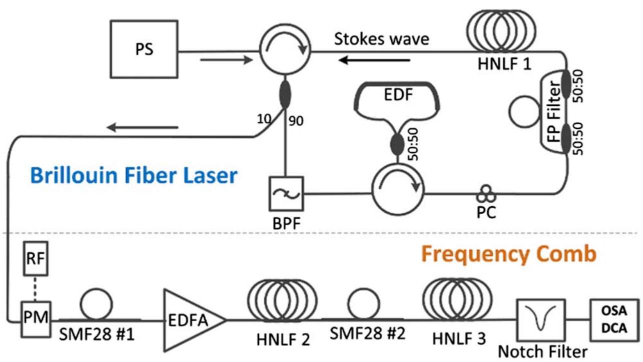

Fig. 1. Experimental setup of the optical comb source. The top section is a single-mode Brillouin laser that generates a CW and narrow linewidth signal. The bottom section converts the CW signal into a frequency comb. PS: primary source; HNLF: highly nonlinear fiber; FP filter: Fabry–Perot filter; EDF: erbium-doped fiber; PC: polarization controller; BPF: band-pass filter; RF: radio frequency signal; PM: phase modulator; EDFA: EDF amplifier; OSA: optical spectrum analyzer; DCA: digital communication analyzer.

Table 1. Specifications of the Highly Nonlinear Fibers Used in the Setup[a]

	L (m)	D (ps/nm/km)	S (ps/nm^2/km)	γ (1/W – km)
HNLF1	200	−0.04	0.02	10.5
HNLF2	1007	−0.04	0.02	10.5
HNLF3	1007	−0.69	0.0074	12.5

[a]Attenuation coefficient is 1 dB/km in all cases.

An optical circulator with an insertion loss of 1 dB delivers the pump inside the resonant cavity. A counter-propagating Stokes wave circulates in the cavity when the pump power exceeds the Brillouin threshold of the HNLF1.

The 200-m-long BFL cavity sustains a free-spectral range (FSR) of 1 MHz. With a Brillouin gain spectrum that has a 30 MHz full width at half-maximum (FWHM), the BFL would be multimode unless additional filtering methods are implemented. The BFL single-mode operation is ensured from a series of two filtering mechanisms that suppress the many longitudinal modes of the compound ring cavity [7]. The filtering mechanisms include an in-fiber Fabry–Perot (FP) filter with a 5-m-long SMF-28 and a Sagnac loop interferometer with a 4-m-long unpumped erbium-doped fiber (EDF). The FSR in the compound ring cavity depends on the lengths of both the primary and secondary cavity. The effective FSR of the compound cavity is given by

$$\mathrm{FSR}_{\mathrm{eff}} = m\mathrm{FSR}_L = p\mathrm{FSR}_l, \tag{1}$$

where m and p are such integers that do not have a common factor, and FSR_L and FSR_l are the FSR of the main and FP cavity, respectively. One way to attain a large effective FSR is to make the length of the FP cavity much shorter than the main cavity [8]. In that case, $\mathrm{FSR}_{\mathrm{eff}}$ becomes approximately equal to FSR_L, which turns out to be 20 MHz in this experiment. Any $\mathrm{FSR}_{\mathrm{eff}}$ from 0.5 to 1 time the Brillouin gain bandwidth ensures that only one longitudinal mode is excited within the Brillouin gain spectrum. Using a standard FP model, the resulting 3 dB linewidth, FSR, and suppression ratio of the compound cavity are found to be 4 MHz, 20 MHz, and 10 dB, respectively.

The unpumped EDF serves as an ultra-narrow filter. In the Sagnac loop, the standing wave generated in the EDF results in spatial hole burning and wavelength-selective saturable absorption [8,9]. The central frequency of this filter automatically tracks the lasing wavelength, ensuring stable single frequency operation [9]. To complete the BFL, an in-cavity bandpass filter with 200 GHz FWHM spectral width is used to suppress the out of band ASE noise. A 10% coupler extracts a fraction of the Brillouin signal for the OFC section.

An RF spectrum of the in-cavity signal is taken to observe longitudinal modes. For this purpose, the output of the 10% coupler is connected to a photodiode and an RF spectrum analyzer with a resolution bandwidth (RBW) of 1 kHz. Figure 2 shows RF spectra of the BFL with and without the use of the EDF and FP filters. The suppression of longitudinal modes using the FP filter and unpumped EDF is apparent in the figure. Longitudinal modes are attenuated by >60 dB, which ensures single-mode operation for the resulting BFL.

The spectrum lineshape of the sources under test is measured using the self-heterodyne method. For this purpose, the signal under test is split in two halves by a 3 dB coupler.

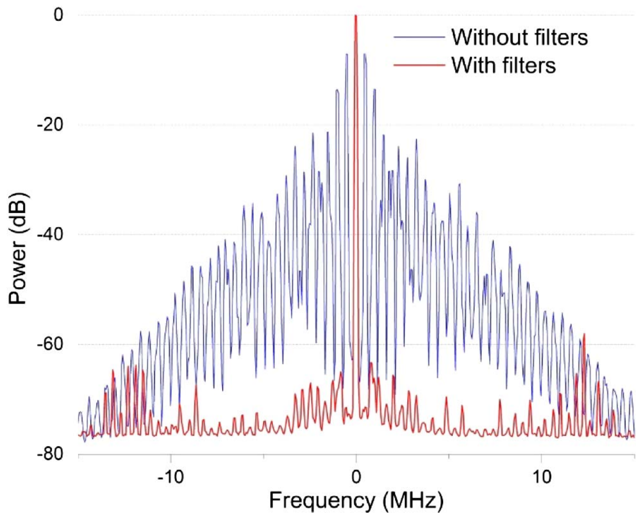

Fig. 2. RF spectra showing the suppression of longitudinal modes by the compound ring cavity inserted in the BFL.

One half is frequency-shifted by 200 MHz by an acousto-optic modulator, and the other half is de-correlated by propagation through a 25-km-long SMF-28 delay fiber. The signal under test and its frequency-shifted copy are then recombined with another 3 dB coupler to generate a beating spectrum at the photodetector. The spectrum of the photodetector current is probed with an electrical spectrum analyzer (ESA). Ideally, a length of hundreds of km of delay fiber is needed to resolve sub kHz linewidth. However, such a long fiber length imposes nonlinearity and frequency noise that prevents a stable beat signal.

Fortunately, true FWHM value can still be extracted from the short-delayed self-heterodyne spectra in two ways. The first way is to fit the spectrum with a Lorentzian lineshape and infer the FWHM from its 20 dB linewidth [10]. Figure 3 shows the RF spectrum as measured for both the PS and the BFL. The lineshape function of both signals is Lorentzian, and their bandwidth is measured at a −20 dB level for best precision. The 20 dB linewidth (FW20dB) of the laser spectrum leads

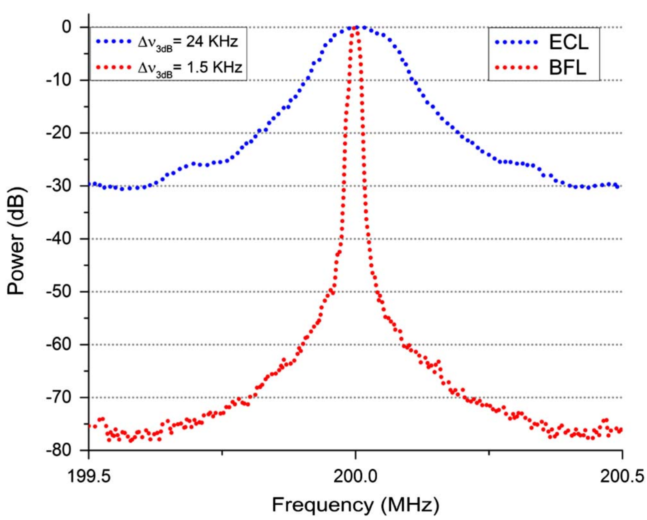

Fig. 3. RF spectra of the PS and BFL signals from self-heterodyne.

to the FWHM linewidth from FWHM = FW20 dB/$2\sqrt{99}$ [11]. The resulting FWHM linewidth of the PS and BFL are 24 kHz and 1.5 kHz, respectively. The linewidth of the BFL is narrower than the one of the PS by a factor of 16, a significant reduction in terms of spectral content of the noise. The BFL thus constitutes an interesting seed to use in a highly coherent optical frequency comb. The second way to extract FWHM linewidth is based on a short delayed self-heterodyne approach using the principle that amplitude difference of the spectrum coherent envelope is related to the linewidth of the laser under test [12]. The linewidth is directly inferred from the power contrast in the first side-lobe of the envelope of the short delayed self-heterodyne spectrum. This approach also leads to a FWHM linewidth of 1.5 kHz, in agreement with the previous result obtained via self-heterodyne.

Figure 4 shows the linewidth of the BFL as a function of output power. The BFL output power is varied by changing the input power of the PS. The BFL has a stable linewidth of 1.5 kHz independent of the output power, thus making it a good candidate to generate a spectrally pure OFC. The laser linewidth is also stable on a time scale of 2 days.

The single longitudinal mode BFL acts as a seed for the comb generation section, itself divided in two stages: the pulse generation stage and the nonlinear mixing stage. In the pulse generation stage, the CW output from the BFL is positively chirped by a phase modulator with an 8 GHz electrical signal followed by propagation into a length of 10.4 km of SMF-28 fiber with anomalous dispersion at a rate of 17 ps/nm-km at a wavelength of 1550 nm. The dispersion compensates the up-chirped portions of the CW signal and stretches the down-chirped portions of the CW signal. This results in a train of pulses at a repetition rate of 8 GHz and pulse width of 18 ps. The frequency pitch of 8.0 GHz optimized for the current setup can be optimized for other values by changing accordingly the length of SMF-28 in the pulse generation stage.

In the nonlinear mixing stage, pulses are amplified by an EDF to an average power of 500 mW and sent to HNLF 2 to trigger a narrowband OFC from four-wave mixing (FWM). This nonlinear process also chirps pulses via self-phase modulation with a maximum nonlinear phase shift of ~5 radians [13]. The chirped pulses are recompressed by a second compression stage that includes a 200-m-length of SMF-28 fiber. Finally, passing through HNLF 3 provides additional FWM and results in a wideband OFC made out of narrow pulses in the time domain. Both HNLF 2 and 3 operate in normal dispersion to avoid modulation instability. The tunable notch filter, with a 50 GHz FWHM, partially blocks the carrier at 1550 nm for temporal side-lobe suppression and spectral equalization [14]. The frequency pitch of the OFC is adjustable by changing the frequency of the electrical signal sent to the phase modulator. The temporal profile and spectrum of the resulting OFC are observed on a digital communication analyzer and an optical spectrum analyzer, respectively.

Figure 5 shows the optical spectrum and temporal profile at the output of the OFC. The optical spectrum is measured with a RBW = 0.80 pm. The OFC has a frequency pitch of 8 GHz and spans over a 15 dB bandwidth of 32 nm. The OSNR is ~30 dB in the central region and drops to ~25 dB near the comb edges. In the time domain, a train of pulses with a FWHM duration of 8 ps is generated after the second compression stage from SMF-28 #2. For an average EDFA output power of 1 W, the carrier wavelength provides the maximum power of −0.50 dBm, whereas the short wavelength edge of the comb provides the smallest power, with −15.50 dBm. By cascading more compression and nonlinear mixing stages, one could further expand the wavelength span of the OFC [15].

Now the question is whether the narrow linewidth of a BFL can be duplicated to every spectral line of the OFC, even at those with a large frequency offset with respect to the carrier frequency. To answer this question, the linewidth of the RF signal generator is measured directly from an ESA, resulting in a FWHM linewidth of $\text{FWHM}_{\text{RF}} = 5$ Hz. Although this linewidth is negligible with respect to 1.5 kHz, the linewidth of an optoelectronic comb scales linearly with comb order contributed by the phase noise of the RF signal [16]. That is, the resulting linewidth of a spectral line of order n is expected to reach $n \times \text{FWHM}_{\text{RF}}$. As a result, the outermost comb of order 275 increases the linewidth by 1.4 kHz, leading to a total linewidth of 2.9 kHz. Despite an increase of the linewidth at high comb order, the resulting linewidths remain advantageously narrower than commercial ECL linewidths of 10–50 kHz.

The linewidth of the OFC is first measured by self-heterodyne. A tunable notch filter isolates groups of six spectral lines, and self-heterodyne is performed on this signal. For six arbitrary spectral lines of the comb taken anywhere in the 8 nm emission spectrum around the carrier wavelength of 1550 nm, the

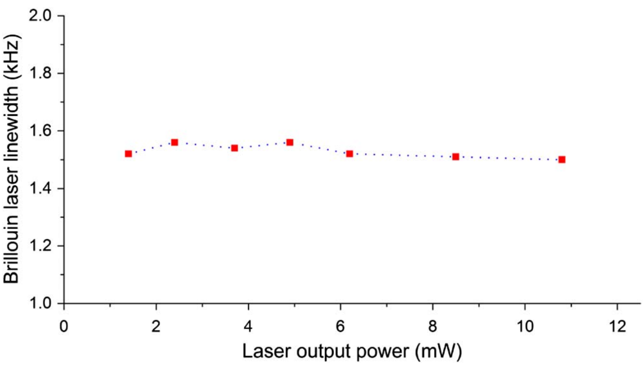

Fig. 4. FWHM linewidth of the BFL as a function of output power.

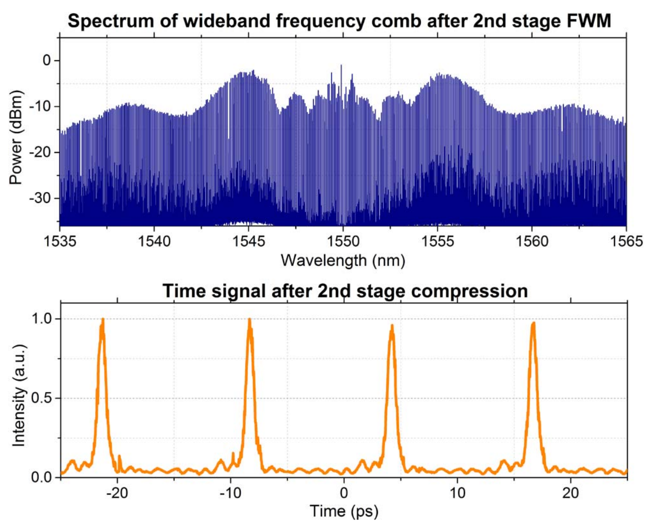

Fig. 5. Spectrum and temporal signal of the optical frequency comb.

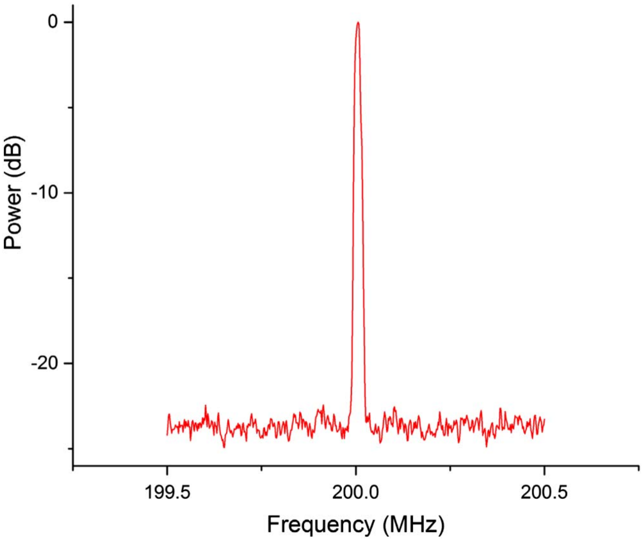

Fig. 6. FWHM lineshape of the OFC within the 8 nm emission spectrum centered at 1550 nm. Taken with an ESA with RBW = 300 Hz.

linewidth measurement consistently leads to 1.5 ± 0.1 kHz. The linewidth measurement approach using subsets of spectral lines has been simulated and confirms that the linewidth is invariant of the number of spectral lines used for the measurement due to their phase matching and proximity to the carrier frequency. Figure 6 shows the typical linewidth of the OFC at ~1550 nm. This experimental measurement shows that low phase noise and mutual coherence are preserved among the individual frequency lines near the carrier frequency and resonates well with other reported work on spectral preservation in OFC [17]. Injection locking with a slave laser is necessary to preserve strict coherence of the comb lines near the comb edge [18].

We have demonstrated the operation of a wideband optical frequency comb with low phase noise by utilizing the linewidth-narrowing effect of Brillouin scattering. The comb has 550 ultra-narrow spectral lines with a FWHM of 1.5–2.9 kHz, covering a spectral span of 32 nm. The system includes a narrow-linewidth optical signal seeded from a Brillouin laser, and the comb is generated in a cavity-free configuration using the parametric gain of nonlinear fibers [19]. With appropriate dispersion engineering of the HNLFs, the span of an OFC as the one presented can be broadened beyond hundreds of nm [20]. The frequency tuning range is only limited by the operating range of the phase modulator. However, generation of a wideband comb with smaller frequency pitch is difficult because pulses have relatively broader pulse width after the compression stage, which results in smaller spectral bandwidth. To generate a smaller frequency pitch OFC with a wider bandwidth, pulse picking or spectral Talbot effect can be used on a comb with high frequency pitch. OFCs with such low phase noise have potential applications in coherent optical communication, precision dual-comb spectroscopy, and high-quality microwave signal synthesis.

Funding. Natural Sciences and Engineering Research Council of Canada (NSERC).

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