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# Cascaded Brillouin fibre lasers coupled to untravelling carrier photodiodes for narrow linewidth terahertz generation

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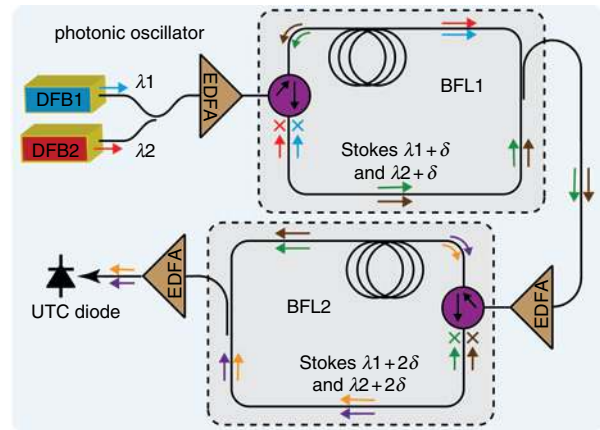
Narrow linewidth terahertz (THz) generation using a cascaded Brillouin fibre laser structure and a untravelling carrier photodiode is investigated. Using two distributed feedback lasers separated by  $>1$  THz with 1 MHz initial linewidth, the use of the cascaded Brillouin laser greatly increases the linewidth reduction factor compared to a single Brillouin laser structure. The linewidth of the realised THz source is found to be  $<100$  Hz at 1014.7 GHz without the use of any active stabilisation of the laser cavity or any microwave reference.

**Introduction:** Terahertz (THz) generation using photomixing techniques is an efficient way to obtain a tunable THz emission, taking advantage of the large tunability of photonics compared to electronics. Moreover, THz generation using electronic multiplication chains suffers from phase noise degradation, increasing with the order of the harmonic generation ( $N$ ). The proposed scheme for narrow linewidth THz generation is efficient for any laser wavelength, and the reported performance is  $<100$  Hz full width at half maximum (FWHM) at 1014 GHz without any stabilisation system.

**Cascaded BFL:** Brillouin fibre lasers (BFLs) have been known for a long time to provide a narrow spectral linewidth emission [1, 2]. The outputted Stokes line is red-shifted by around 10 GHz (at 1550 nm) and might be narrower by a factor of  $\sim 100$  to  $\sim 1000$  with respect to its pump. This is of particular interest for THz wave generation using photomixing. Usually, however, the pump must be carefully phase-locked to the BFL's cavity. This is detrimental for applications because it limits the number of arbitrary wavelengths that can seed the BFL. To overcome this difficulty, a new BFL cavity has been recently designed [3, 4]. The pump is unconditionally injected through an optical circulator, see Fig. 1. It performs only one single turn in the cavity so that it is not resonant. Conversely, the back-propagated Stokes line is free to circulate inside the cavity. The number of turns is only limited by the cavity loss. This architecture allows one to inject an arbitrary number of pump lines (provided they are separated by a frequency several times the value of the Brillouin linewidth of  $\sim 20$  MHz), which is well suited for THz wave generation by frequency difference. Furthermore, as the pump power is increased, the apparition of a second-order Stokes line is forbidden because it would be co-propagating with the pump and blocked by the circulator as well. Therefore, there is always one single Stokes line per pump wavelength. Lastly, the emission is tunable through the adjustment of the two distributed feedback (DFB) laser diode pumps. The generation of highly coherent THz wave,  $\sim 1$  kHz FWHM at 316 GHz, has been demonstrated with such a dual-frequency BFL [5], with  $\sim 500$  narrowing factor. In this Letter, the FWHM of the initial DFB lasers was 1 MHz and we show that, by cascading two BFLs, it is possible to increase this factor up to  $\sim 10\,000$  at a frequency as high as 1 THz.

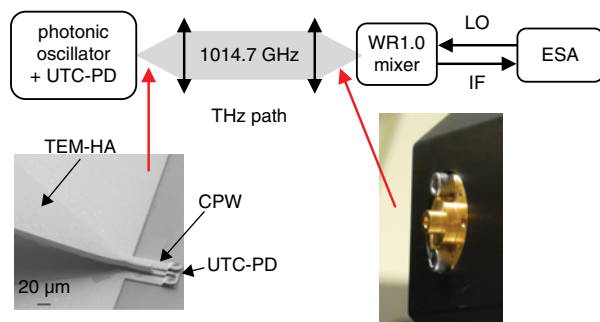
**THz generation:** The dual-mode signal coming from the cascaded BFL is amplified using an erbium-doped fibre amplifier (EDFA), feeding a untravelling carrier photodiode (UTC-PD) device, which realises the photonic-to-THz conversion. Owing to a graded composition of the absorption layer in the UTC-PD, no bias is required to use the UTC-PD. This quasi-optic photomixer is integrated with a wideband transverse electromagnetic horn antenna, working in a broadband range, i.e. from 100 to 1000 GHz [6]. The THz path is composed of two polymer lenses: the first one collects the signal from the emission antenna and the second one focuses the THz beam inside the receiver. The transmission distance was fixed to  $\sim 50$  cm.

**Experimental setup:** The experimental setup was composed of the THz emitter (photonic oscillator + quasi-optic UTC-PD), the THz optics and the electronic receiver, as shown in Fig. 2.



**Fig. 1** Cascaded BFL structure

After being amplified by EDFA1, emission of two DFB laser diodes (DFB1 and DFB2) seeds first BFL cavity (BFL1). Two narrow Stokes lines are generated and seed second BFL to be further narrowed. Resulting output is amplified and focused on UTC photodiode producing 1 THz line with  $<100$  Hz FWHM



**Fig. 2** Experimental setup: photonic oscillator + UTC-PD, THz optics and electronic receiver: WR1.0 (750–1100 GHz) mixer

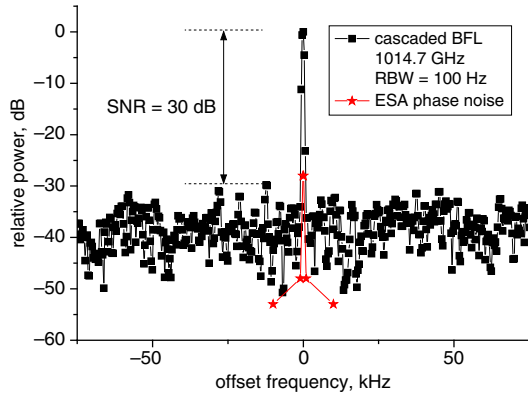
Scanning electron microscope view of UTC-PD and photograph of entrance of receiver (horn antenna)

**THz reception:** The THz signal is then collected in a WR1.0 (750–1100 GHz) sub-harmonic mixer (SHM) from Radiometer Physics GmbH, coupled to an electrical spectrum analyzer (ESA), an FSU 67 from Rodhe&Schwarz. The SHM works in the WR 1.0 waveguide band (750–1100 GHz) and performs a room-temperature and frequency resolved detection. In this device, the 1014.7 GHz signal is mixed with the  $N$ th harmonic of the local oscillator (LO) of an ESA to produce an intermediate frequency at 404.4 MHz quantified by the ESA.

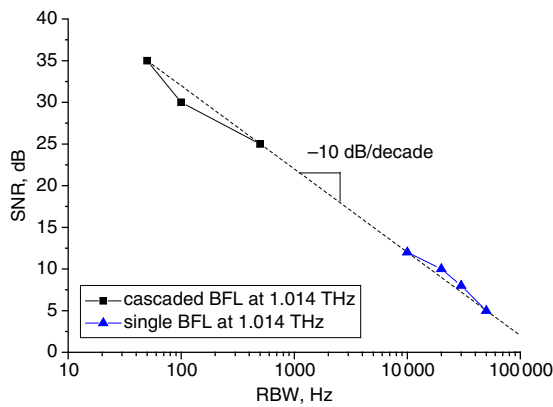
**Results:** Fig. 3 gives the detected spectrum using a 700  $\mu$ A photocurrent in the UTC-PD device, without any bias voltage. The instantaneous (sub-second) measured FWHM is  $<100$  Hz. Moreover, over the 2.4 s sweep time of the measurement, the frequency jitter was found to induce an apparent 500 Hz linewidth. This kind of photomixer (with a 2  $\mu$ m diameter active area) has been shown to deliver 0.46  $\mu$ W power level at 1 THz [7] for 2.5 mA photocurrent and a  $-0.4$  V bias. Because the THz photomixer used in this case was 3  $\mu$ m in diameter and was not biased, the generated power is estimated to be  $<10$  nW for the actual 0.7 mA photocurrent used in this Letter. However, as the primary goal of this Letter was to characterise the spectral content of the THz line produced by the photonic oscillator rather than generating high powers at 1 THz, we did not use higher photocurrents during the experiments to preserve the lifetime of the UTC-PD device.

The phase noise of the FSU local oscillator used to pump the SHM is  $-89/-109/-114$  dBc/Hz (1 Hz bandwidth) at 100 Hz/1 kHz/10 kHz carrier offset, respectively. Thus, according to the multiplication number  $N$  of the harmonic mixer, the effective phase noise of the multiplied signal inside the harmonic mixer is increased by at least  $20 \log(N) = 40.6$  dB. Taking into account the 100 Hz resolution bandwidth of the spectra, the ESA phase noise at 1014.7 GHz is  $-28/-48/-53$  dBc at 100 Hz/1 kHz/10 kHz, respectively. These values are reported in Fig. 3 to highlight that at this high-frequency range, the phase noise of the photonic-based source is quite close (10–15 dB), but still higher than the multiplied LO source used for the detection.

To highlight the very low FWHM of the dual-mode optical signal provided by the cascaded BFL structure, we show in Fig. 4 the evolution of the signal-to-noise ratio (SNR) for different resolution bandwidth (RBW). Up to 50 Hz RBW, the SNR increases with a constant slope of 10 dB per RBW decade; from a few decibels using a single BFL structure with 50 kHz RBW and up to 35 dB for the lowest RBW tested with the cascaded BFL structure. For RBW < 50 Hz, the SNR was saturating as the 1014.7 GHz line was decreasing with the RBW reduction. This highlights that the instantaneous linewidth is < 100 Hz.



**Fig. 3** Detected spectrum at electrical mixer output (RBW = 100 Hz) Stars symbols indicate phase noise of ESA at 1014.7 GHz (− 28 dBc at 100 Hz, − 48 dBc at 1 kHz, − 53 dBc at 10 kHz). Sweep time = 2.4 s



**Fig. 4** SNR of THz detected spectrum with single and cascaded Brillouin laser structure for 700  $\mu$ A current in UTC-PD

Dashed line represents theoretical evolution of SNR against RBW

**Conclusions:** A photonic oscillator composed of a cascaded Brillouin laser has been proposed to produce narrow bandwidth THz lines, up to 1.014 THz using a broadband quasi-optic UTC-PD device. The FWHM obtained is better than 100 Hz and the frequency drift over a few seconds time windows is better than 500 Hz. However, this kind of long-term frequency drift could be compensated for using feedback

loops (active stabilisation) associated with a stable electrical frequency reference.

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One or more of the Figures in this Letter are available in colour online.

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