Coherent terahertz-wave generation based on optical frequency division via an integrated dissipative Kerr soliton comb

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Optical frequency division (OFD) through an optical frequency comb has been employed for the generation of microwave signals with extraordinary phase noise performance [1]. Although its extension to millimeter- and terahertz-wave domain is of great interest for applications such as rotational spectroscopy and wireless communication, the demonstration is hindered by necessity of ultrafast optoelectronic devices and performing self-referencing with high repetition rate (i.e., low energy) pulses. In this study, we demonstrate OFD of an optically-carried 3.6 THz reference via an integrated dissipative Kerr soliton (DKS) comb, and generate a 300 GHz wave with a record-low phase noise of −100 dBc/Hz at 10 kHz Fourier frequency.

Fig. 1(a) depicts a schematic drawing of a setup for the OFD. A DKS comb is obtained through cascaded four wave mixing inside a silicon nitride (SiN) ring resonator on a chip. The DKS is split into two paths; one is used for wave generation and measurement, and one is employed for stabilizing the DKS. On the latter path, two optical lines of the DKS with frequency separation of about 3.6 THz ($f_1 = nf_{\rm rep}+f_{\rm CEO}$ and $f_2 = mf_{\rm rep}+f_{\rm CEO}$) are spectrally filtered and interfered with two optical reference lines with a similar frequency separation (ν_{s1} and ν_{s2}), where the phase noise of the optical references are sufficiently suppressed through stimulated Brillouin scattering in a fiber ring cavity. The generated two beat notes ($f_1 - \nu_{s1}$ and $f_2 - \nu_{s2}$) are interfered in a low barrier Schottky diode (LBSD), and gives an intermediate signal. Applying the phase error of the intermediate signal to the DKS via pump frequency modulation with a single sideband modulator (SSBM) leads to repetition frequency noise of $<\delta f_{\rm rep}>^2 = <\delta(\nu_{s1}-\nu_{s2})>^2/(n-m)^2$. By doing this, we implement OFD while avoiding use of the self-referencing technology at the expense of relatively small division factor (21.6 dB in terms of power spectral density). Figure 1(b) shows a setup for the wave generation and characterization. A 300 GHz wave is obtained by detecting the DKS's repetition frequency with an ultrafast uni-traveling-carrier photodiode (UTC-PD). To measure phase noise of the 300 GHz wave, another 300 GHz wave, generated from two lines of an electro-optic comb driven by a 10 GHz dielectric resonant oscillator (DRO), is mixed with the DKS-based 300 GHz wave. The phase error of the intermediate frequency of the two waves is applied to the DRO through a PID loop. As a result, the DRO is phase-locked to the DKS-based 300 GHz and gives its down-converted phase noise. Figure 1(c) presents measured phase noise. The DKS's repetition frequency noise (black line), which is characterized by a two-wavelength delayed self-heterodyne interferometer (TWDI) before the wave generation, faithfully follows the calibrated optical reference noise (red line) for Fourier frequencies of < 10 kHz, while the in-loop noise of the PID control (blue line) limits the noise level for the higher offset frequencies. The measured 300 GHz wave noise (green line) exhibits same noise level as the repetition frequency noise except Fourier frequencies between about 7 kHz and 100 kHz, where the noise is limited by the measurement system. The measured phase noise at 10 kHz Fourier frequency is −108 dBc/Hz for the repetition frequency and −100 dBc/Hz for the 300 GHz wave. To the best of our knowledge, these values are 18 dB and 10 dB lower than 300 GHz wave noise reported in peer-reviewed papers, respectively [2]. In the presentation, frequency stability of the source is also discussed.

In conclusion, we perform OFD for the first time in the terahertz wave domain by using the integrated DKS and the 3.6 THz optically-carried reference. The generated 300 GHz wave is evaluated with the devised system and shows the measurement-limited phase noise of -100 dBc/Hz at 10 kHz, which is one decade lower than that for the best oscillator in the frequency domain.

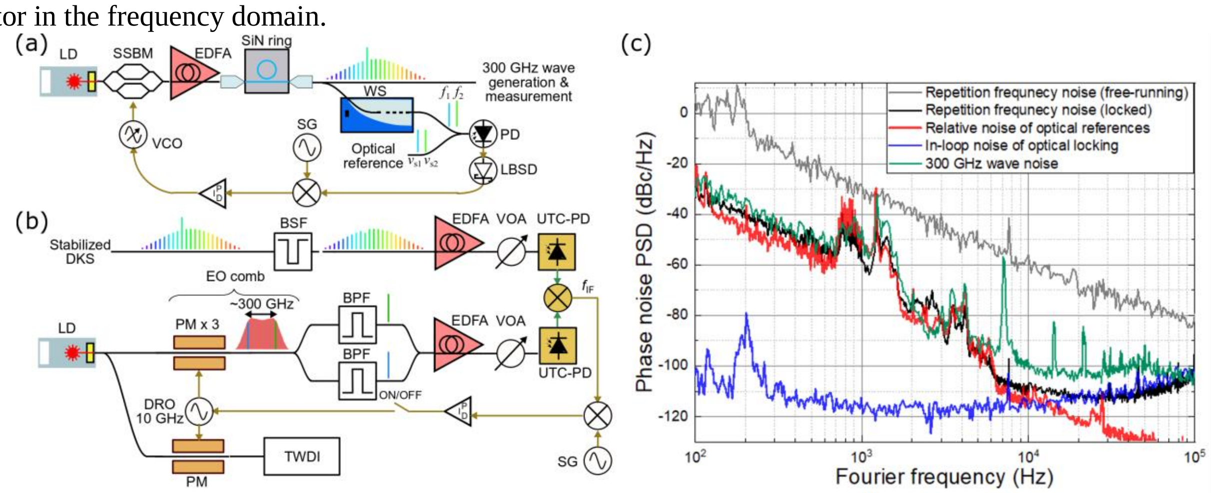

Fig. 1: (a) Schematic drawing of a setup for the OFD via a DKS comb. (b) Schematic drawing of a setup for the 300 GHz wave generation and characterization. (c) Phase noise of the stabilized DKS and the 300 GHz wave. LD: laser diode. EDFA: erbium-doped fiber amplifier. WS: waveshaper. PD: photodiode. SG: signal generator. VCO: voltage controlled oscillator. BSF: bandstop filter. VOA: variable optical attenuator. PM: phase modulator. BPF: bandpass filter.

[1] X. Xie *et al*., Nat. Photonics **11**, 44–47 (2017). [2] Y. Li *et al*., Opt. Lett. **44**, 359–362 (2019).