

Towards fast spectroscopy using a practical all-fibre GHz dual-comb laser

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Abstract

A single-cavity all-fibre laser operating at GHz rates is demonstrated as a promising approach for fast spectroscopy. Multimode-interference-based spectral filtering in the laser enables dual-wavelength mode-locked pulse generation (thus, dual-comb emission) with a 148 kHz repetition rate difference. The GHz dual-comb laser exhibits excellent stability and can be used for outdoor measurements.

Keywords: Spectroscopy, All-fibre, Dual-comb laser

Optical frequency combs have revolutionised precise spectroscopy, metrology, and imaging^{1,2}. Among comb-based applications, dual-comb spectroscopy (DCS), which uses multiheterodyne beat between two combs with slightly different repetition rates, has emerged as a powerful technique for fast, high-resolution, and moving-part-free spectroscopy². DCS has been implemented from near-ultraviolet to mid-infrared^{3,4} and has enabled many important applications, including chemical kinetic diagnostics⁵, 100-km-scale greenhouse-gas emission monitoring⁶, and the physio-chemical analysis of supersonic pulsed jets⁷.

Despite significant progress, DCS still faces challenges in simultaneously realising a broad measurement bandwidth and fast measurement speed. This is because the measurement bandwidth is limited to $\Delta\nu \leq f_r^2/2\delta f_r$, where f_r is the repetition rate (i.e. the comb line spacing) and δf_r is the repetition rate difference between two combs that determines the fastest measurement rate $1/\delta f_r$. To achieve this goal, a large comb-line spacing is required; however, an excessively large spacing leads to degraded spectral resolution. Therefore, DCS with a GHz-level repetition rate

is of significant interest for balancing measurement speed and spectral resolution^{8–11}. Although dual-microcomb measurements with GHz resolution have been demonstrated^{4,12}, most microcombs usually operate with >10 GHz line spacings. In contrast, most mode-locked lasers have repetition rates below hundreds of MHz. Realizing GHz dual-comb systems remains technically challenging.

Most of the reported mode-locked laser-based DCS systems use two independent lasers^{5,9}. Electronic feedback loops and external references are usually required to maintain their mutual coherence². The GHz single-cavity dual-comb laser is a compelling alternative for simplifying DCS systems¹³. Because the two combs share the same cavity, most of the technical noise can be cancelled to enhance the relative stability. Several multiplexing methods, including polarization¹⁴, wavelength¹⁵, propagation direction¹⁶, and spatial dimension¹⁷, are feasible for introducing a repetition rate difference between these two pulse trains. Indeed, a polarisation-multiplexed dual-comb laser with a GHz free space cavity has been demonstrated and used in DCS¹⁸. However, there are still no reports on GHz single-cavity dual-comb generation in compact all-fibre lasers.

In a recently published paper in *Light: Science & Applications*, Ling et al. demonstrated wavelength multiplexing in a GHz all-fibre laser with a few-mode gain

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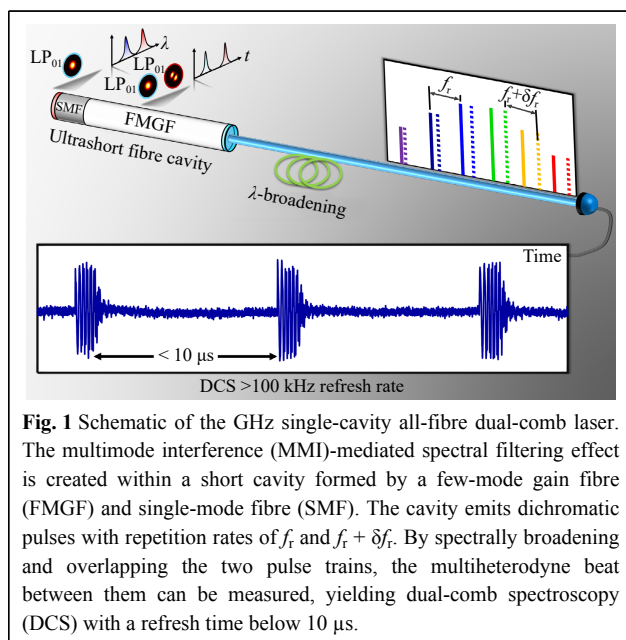


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fibre (FMGF, supporting the LP₀₁ and LP₁₁ mode)¹⁹. The dual-wavelength mode-locked laser emits two pulse trains at a rate of 1.093 GHz, with a repetition rate difference $\delta f_r = 148$ kHz. The repetition rate difference exhibits excellent stability, with an Allan deviation of 101.7 mHz @ 1 s. The short cavity supports the relatively large δf_r and 6.75 μ s single-frame measurement time, which is the highest for a dual comb emitted from a single fibre laser cavity to date.

Multimode interference (MMI)²⁰ between the FMGF and single-mode fibre (SMF) within the cavity enables dual-wavelength mode locking (Fig. 1). The Fabry-Pérot (FP) laser cavity comprises only one piece of SMF and one piece of FMGF. The unfolded nature of the FP cavity creates an “SMF-FMGF-SMF” structure and results in MMI-based spectral filtering. The frequency spacing of the MMI-based filter can be controlled by the length of the FMGF. Using a relatively large spectral filtering spacing, the soliton trapping effect between the two pulse trains can be broken and dichromatic pulse emission can be attained. Finally, the two pulse trains are spectrally broadened in a photonic crystal fibre to overlap them spectrally for DCS (Fig. 1).

The robustness and fast measurement capability of the GHz dual-comb laser were carefully examined through outdoor experiments. For example, the team measured the transient wavelength shift of an array of fiber Bragg gratings induced by shockwaves emitted from firecracker explosions. The reliability of the short all-fibre laser cavity and large δf_r bode well for deploying the demonstrated GHz dual-comb laser for field measurements. The laser



operated at ~ 1060 nm, but could be transferred to other spectral ranges by nonlinear frequency conversion. By further optimising the laser cavity, both the pulse energy and δf_r can be improved, which can enable a higher signal-to-noise ratio in DCS and faster measurement rates. This should create exciting opportunities for interdisciplinary applications.

Data availability

All data are available from the corresponding authors upon reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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References

- Picqué, N. & Hänsch, T. W. Frequency comb spectroscopy. *Nature Photonics* **13**, 146-157 (2019).
- Coddington, I., Newbury, N. & Swann, W. Dual-comb spectroscopy. *Optica* **3**, 414-426 (2016).
- Xu, B. X. et al. Near-ultraviolet photon-counting dual-comb spectroscopy. *Nature* **627**, 289-294 (2024).
- Bao, C. Y. et al. Architecture for microcomb-based GHz-mid-infrared dual-comb spectroscopy. *Nature Communications* **12**, 6573 (2021).
- Hoghooghi, N. et al. GHz repetition rate mid-infrared frequency comb spectroscopy of fast chemical reactions. *Optica* **11**, 876-882 (2024).
- Han, J. J. et al. Dual-comb spectroscopy over a 100 km open-air path. *Nature Photonics* **18**, 1195-1202 (2024).
- Long, D. A. et al. Nanosecond time-resolved dual-comb absorption spectroscopy. *Nature Photonics* **18**, 127-131 (2024).
- Herman, D. I. et al. Squeezed dual-comb spectroscopy. *Science* **387**, 653-658 (2025).
- Chang, P. et al. Mid-infrared hyperspectral microscopy with broadband 1-GHz dual frequency combs. *APL Photonics* **9**, 106111 (2024).
- Hoghooghi, N., Cole, R. K. & Rieker, G. B. 11- μ s time-resolved, continuous dual-comb spectroscopy with spectrally filtered mode-locked frequency combs. *Applied Physics B* **127**, 17 (2021).
- Yang, R. A. et al. A GHz fiber comb on silica. Print at <https://arxiv.org/abs/2503.16249> (2025).
- Bao, C. Y., Suh, M. G. & Vahala, K. Microresonator soliton dual-comb imaging. *Optica* **6**, 1110-1116 (2019).
- Liao, R. Y. et al. Dual-comb generation from a single laser source: principles and spectroscopic applications towards mid-IR—A review. *Journal of Physics: Photonics* **2**, 042006 (2020).
- Zhao, X. et al. Polarization-multiplexed, dual-comb all-fiber mode-locked laser. *Photonics Research* **6**, 853-857 (2018).
- Zhao, X. et al. Picometer-resolution dual-comb spectroscopy with a free-running fiber laser. *Optics Express* **24**, 21833-21845 (2016).
- Nakjima, Y., Hata, Y. & Minoshima, K. High-coherence ultra-broadband bidirectional dual-comb fiber laser. *Optics Express* **27**, 5931-5944 (2019).
- Pupeikis, J. et al. Spatially multiplexed single-cavity dual-comb laser. *Optica* **9**, 713-716 (2022).
- Link, S. M. et al. Dual-comb spectroscopy of water vapor with a free-running semiconductor disk laser. *Science* **356**, 1164-1168 (2017).
- Ling, L. et al. Practical GHz single-cavity all-fiber dual-comb laser for high-speed spectroscopy. *Light: Science & Applications* **14**, 133 (2025).
- Zhao, K. J. et al. Free-running dual-comb fiber laser mode-locked by nonlinear multimode interference. *Optics Letters* **44**, 4323-4326 (2019).