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Special Collection: State-of-the-Art and Future Directions in Optical Frequency Comb Sources, Enabling Technologies, and Applications

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INTRODUCTION

Optical frequency combs based on mode-locked systems have emerged as a powerful and enabling technology in the context of optical and electronic synthesis and in precision timing. Frequency combs, which combine ultrafast laser technology and single frequency laser stabilization techniques, permit the generation of highly stable optical and microwave optical signals for high-resolution time and frequency applications.[1] Originally realized to help in the characterization and development of optical atomic clocks, the diversification of optical frequency comb sources and optical references, as well as novel techniques in wavelength conversion, has significantly expanded their versatility and application space.[2]

In this special topical collection, we delve into the latest advancements and applications of frequency combs, showcasing their diverse utility and highlighting the cutting-edge research driving innovation in this field. From "dual-comb" laser ranging,[3] to terahertz photonics[4] and molecular referencing,[5] optical communications and to space-based time/frequency dissemination,[6] each article offers technical insights into the impact and innovation that frequency comb technology brings to each field.

SUMMARY OF AREAS COVERED

Highlighted within this special collection are innovative studies using bulk mode-locked lasers, including the investigation of Caldwell *et al.* into space-based high-precision time and frequency dissemination utilizing optical frequency combs,[6] the development of Schmid *et al.* of a low-noise, high-power, solid-state mode-locked laser for application in extreme ultraviolet (XUV) generation and low-noise optical synthesis,[7] and the report of a record optical synthesis at the 10^{-22} level by Shi *et al.*[8]

The move toward compact, commercial, and fieldable systems has seen concerted research efforts in microresonator-based frequency combs (microcombs),[9–11] quantum cascade lasers (QCLs),[12–14] electro-optic combs,[15–17] and compact optical references.[18,19] Notably, advancements in compact comb sources by Jeon *et al.* using all-fiber references have enabled applications with exceptional stability and fractional instability as low as 10^{-14}.[19] Greenberg *et al.* describe the development of a THz molecular reference using a microcomb source.[5] Tran *et al.* describe impressive results in a highly tunable, high sensitivity QCL comb operating as a molecular spectrometer in the near- to mid-IR range.[20]

Furthermore, the exploration of scan-free dual-comb systems has facilitated rapid progress in a multitude of applications explored here.[14,21–24] For instance, Westberg *et al.* have explored the application of dual-comb quantum cascade lasers for open-air trace gas sensing,[14] while Giorgetta *et al.* utilize programmable frequency combs for adaptable spectroscopy and hyperspectral imaging.[24]

In parallel, the demand for higher repetition rate combs for applications such as radio-frequency photonics and astronomical spectrograph calibration has led to the development of electro-optic (eo) modulation combs and microresonator-based combs. Cai *et al.* investigate the nonlinear broadening of an electro-optic frequency comb optimized for low optical phase noise operation,[15] while Sekhar *et al.* demonstrate high peak power at high repetition rates using an integrated waveguide-based Fabry–Pérot resonator.[16]

In addition, Bunel *et al.* showcase significant broadening in a fiber Fabry–Pérot resonator, akin to what is achieved with integrated microresonator sources.[25] Wildi and colleagues present an all-optical method to injection lock a microcomb line to an external reference laser, demonstrating optical frequency division and repetition rate phase noise reduction.[11] Similarly, Liu *et al.* achieve optical frequency division using two-point locking and a microfabricated air-gap cavity, resulting in ultralow-phase noise microwaves.[18] Finally, Adhi *et al.* introduce a fiber-cavity laser configuration for mode-locking, offering control over pulse trains across different time scales.[26] Through selectively filtering cavity modes, they demonstrate a transition from nanosecond pulse bursts to coexisting nanosecond and picosecond pulses.

CONCLUSIONS

This collection mirrors the breadth and depth in frequency comb technology, highlighting its role in precision frequency synthesis and metrology across a vast spectrum—from the microwave to the XUV ranges. From space-based time and frequency dissemination to RF photonics, from dual-comb laser ranging to adaptable spectroscopy, each article showcased within this collection illuminates the transformative impact and boundless potential of optical frequency combs. As research continues to push the boundaries of compactness, stability, and versatility, the horizon for frequency comb applications expands ever further, promising continued innovation and scientific discoveries in the years to come.

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AUTHOR DECLARATIONS

Author Contributions

Tara Fortier: Writing – original draft (equal); Writing – review & editing (equal). **Victor Torres-Company**: Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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