

Recent progress on mid-infrared and terahertz dual-comb spectroscopy

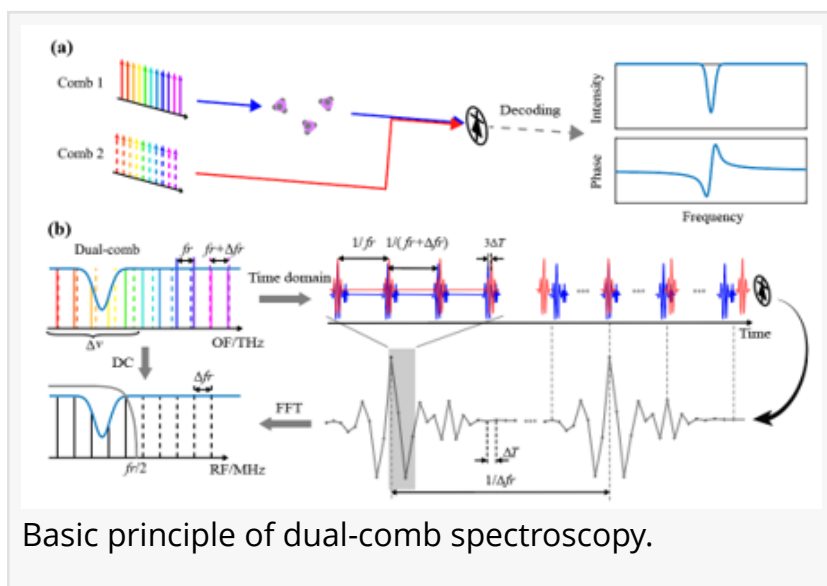
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Dual-comb spectroscopy combines the precision of optical frequency combs with rapid spectral acquisition. Extending this approach to the mid-infrared and terahertz regions, however, presents challenges in generating broad, coherent combs. This review surveys recent advances in optical comb technologies for these important molecular spectral regions, highlights their strengths and limitations, and outlines future directions toward broader spectral coverage, higher sensitivity, greater stability, and more compact and integrated systems.

Optical frequency combs (OFCs) are light sources that contain many evenly spaced and precisely controlled spectral lines. Their broad spectral coverage and high frequency accuracy make them powerful tools for measuring and identifying molecules. Dual-comb spectroscopy (DCS) uses two slightly different frequency combs to rapidly record detailed optical spectra, combining high precision with fast measurement. This capability has enabled a wide range of applications, including atmospheric monitoring, trace-gas detection, combustion diagnostics, industrial process monitoring, biomedical analysis and fundamental studies of molecules.

The mid-infrared and terahertz regions are particularly valuable for molecular spectroscopy. The mid-infrared region contains strong molecular vibrations and is often regarded as a “molecular fingerprint” region, where different molecules produce characteristic absorption patterns. The terahertz region provides complementary information from molecular rotations and other low-energy motions. Together, these spectral regions offer powerful means for identifying molecules and probing their properties.

However, producing broad and stable frequency combs in the mid-infrared and terahertz



Basic principle of dual-comb spectroscopy.

regions remains challenging. Compared with the visible and near-infrared regions, there are fewer suitable lasers and optical materials, while losses and limitations in light conversion can further restrict performance. Researchers have therefore developed a range of approaches, including nonlinear optical conversion, optical parametric devices, quantum cascade lasers and integrated photonic technologies. These approaches offer different advantages in terms of spectral coverage, stability, power and system complexity. Understanding their respective strengths and limitations is essential for developing faster, more sensitive and more practical dual-comb spectrometers for molecular sensing and other applications.

The research groups of Prof. Heping Zeng and Prof. Ming Yan at East China Normal University, together with Prof. Hua Li's group at the Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, and Prof. Min Li's group at the University of Shanghai for Science and Technology, review recent advances in mid-infrared and terahertz dual-comb spectroscopy. Beginning with the fundamental principles of DCS (Figure 1), the review systematically summarizes major technological approaches, representative advances, and future directions in these two spectral regions.

For mid-infrared DCS, the review focuses on several major approaches to dual-comb generation, including difference-frequency generation, optical parametric oscillators, quantum cascade lasers, and integrated photonic platforms. These technologies offer complementary advantages and involve different trade-offs. Difference-frequency generation can extend mature near-infrared comb technology into the mid-infrared while providing broad wavelength coverage and high coherence. Optical parametric oscillators offer high output power and broad tunability, whereas quantum cascade lasers directly generate combs in the molecular fingerprint region and enable compact, electrically driven systems. Integrated photonic technologies, including microresonators and nonlinear waveguides, are further promoting system miniaturization and integration. The review highlights that practical systems must balance spectral coverage, resolution, output power, acquisition speed, and system complexity.

For terahertz DCS, the review summarizes major approaches based on femtosecond lasers, electro-optic frequency combs, and terahertz quantum cascade lasers. Femtosecond-laser-based approaches provide broad spectral coverage and densely spaced comb lines, while electro-optic combs offer high frequency stability and flexible electronic control. Terahertz quantum cascade lasers provide relatively high output power and strong potential for compact systems. Recent advances in self-detection and on-chip integration have further enabled quantum cascade laser devices to combine the functions of light source, local oscillator, and detector, opening new possibilities for simpler and more compact terahertz spectrometers.

Across the mid-infrared and terahertz regions, the review identifies several common challenges, including broader spectral coverage, more sensitive broadband detection, long-term mutual coherence, and improved system integration. It also highlights emerging quantum technologies as promising approaches for detecting weak spectroscopic signals and further enhancing the capabilities of DCS.

Future DCS is expected to advance toward broader spectral coverage, higher sensitivity, improved long-term stability, and greater system integration. Continued progress in integrated photonics, quantum-enhanced detection, self-detection, and digital coherence correction could further enhance performance while reducing system complexity. These developments are expected to accelerate the transition of mid-infrared and terahertz DCS from precision laboratory instruments to practical tools for environmental monitoring, industrial sensing, biomedical analysis, and molecular identification.

Keywords: optical frequency combs, dual-comb spectroscopy, mid-infrared spectroscopy, terahertz spectroscopy

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The research teams led by Prof. Heping Zeng and Prof. Ming Yan focus on advanced precision spectroscopy and imaging technologies, with particular emphasis on mid-infrared dual-comb spectroscopy (DCS) and comb-enabled hyperspectral imaging for applications such as trace-gas detection and remote sensing. Their collaboration with Prof. Hua Li and Prof. Min Li has further extended DCS into the important terahertz (THz) region, contributing to advances in THz metrology and spectroscopy. Together, these teams have co-published more than 100 research papers in leading journals, including Nature Photonics, Nature Communications, and Light: Science & Applications, and have received the Shanghai Technical Invention First Prize (2024) and the First Prize for Scientific and Technological Progress in Chongqing (2024).

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