

# Sub-Picometer Resolution Spectroscopy With Interleaved Recirculating Frequency-Shifting Loop Combs

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**Abstract:** We proposed and demonstrated a novel interleaved dual-comb spectroscopy technique based on a dual-recirculating frequency-shifting loop (RFSL), achieving sub-picometer resolution over an effective measurement bandwidth of more than 0.5 THz. The dual combs were generated by seeding a dual-RFSL with the same continuous-wave (CW) laser, eliminating the requirement for complex phase-locking systems. The dual-RFSL architecture produced flat-topped dual-comb spectra spanning over 5 nm, with line spacings of 16 GHz and 15.999 5 GHz, respectively. A stepped-frequency tunable laser was demonstrated via modulation sideband optical injection locking, where the tuning frequency was precisely regulated by an RF signal applied to the electro-optic (EO) modulator, enabling arbitrary high-precision frequency stepping of the seed laser. By performing interleaved scanning of the dual-comb source with step sizes of 500 MHz (4 pm) and 100 MHz (0.8 pm) over 32 and 160 steps, respectively, we obtained the transmission spectrum of a fiber Bragg grating (FBG) over a bandwidth of 641.5 GHz and the absorption spectrum of the H<sup>13</sup>C<sup>14</sup>N gas over a bandwidth of 536.5 GHz. The results exhibited excellent agreement with the reference spectrum, demonstrating that this method provided a simple and effective spectroscopic approach for gas sensing and environmental monitoring.

**Keywords:** Dual-comb spectroscopy; recirculating frequency-shifting loop; optical frequency combs; interleaved frequency comb

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## 1. Introduction

The optical frequency comb (OFC) represents a major breakthrough in the laser technology, producing a series of discrete, evenly spaced spectral lines that enable a precise link between the microwave and optical frequency domains [1–4]. This unique property has enabled OFCs to achieve

unprecedented accuracy in time and frequency measurement, and has led to their successful applications in diverse fields, including optical communications [5], laser ranging [6], and precision spectroscopy [7]. Over the past few decades, the emergence of OFCs revolutionized spectroscopy and several comb-based spectroscopic techniques have

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been developed, including the Fourier transform spectroscopy [8], direct comb spectroscopy using spectrometers [9, 10], and virtual imaging phase array (VIPA)-based spectroscopy [11]. Furthermore, unique dual-comb spectroscopy (DCS) stands out for its superior performance in achieving both high speed and high accuracy in measurement. It operates by beating two OFCs with slightly different repetition rates, enabling the retrieval of each frequency component in the radio frequency (RF) domain using a single photodiode detector, thereby accessing the spectral information encoded on the combs. Traditional dual-comb systems often rely on two independent mode-locked lasers, which must be carefully phase-locked to maintain coherence. Establishing coherence between two independent optical combs typically requires complex phase-locking circuits [12, 13]. In contrast, the emergence of electro-optic frequency combs (EOFCs) simplifies this process, as two combs can be generated from the same CW laser using two electro-optic (EO) modulators [14]. The comb line spacing is determined by the RF signal driving the EO modulators, while the central frequency is set by the CW laser. This dual-comb scheme, seeded by a common laser, shares similarities with self-referenced or offset-frequency cancellation techniques [15], offering inherent mutual coherence and substantially reduced system complexity. Nevertheless, limited by the bandwidth of the modulators, broadening the bandwidth of EOFCs usually requires cascading multiple modulators and high-power RF signal amplifiers, and generating a flat-topped EOFC necessitates precise phase control [16], which significantly raises power consumption and incurs prohibitively high costs.

The recirculating frequency shifting loop (RFSL) offers an attractive alternative by accumulating comb lines via circulating a CW laser signal through a single frequency-shifting modulator. The RFSL is a simple ring cavity structure primarily composed of a frequency-shifting modulator, a loss-compensating

amplifier, and a bandpass filter to suppress the amplified spontaneous emission (ASE). It is capable of generating an OFC through continuous-wave injection, as well as producing pulse sequences equally spaced in both time and frequency domains via pulsed optical excitation. Currently, RFSs have been widely used in applications, such as absorption spectroscopy [17–20], ranging [21], and arbitrary waveform generation [22]. The RFSL can easily produce flat-topped combs whose line spacing is determined by the RF applied to the frequency-shifting modulator. Such a flat optical frequency comb source is critically important for precision molecular spectroscopy, as it significantly improves spectral background fitting, facilitates line shape normalization, and enhances both the dynamic range and signal-to-noise ratio of measurement [23]. The RFSL based on frequency-shifting modulators has been shown to generate a broadband flat-topped OFC by leveraging higher modulation frequencies [24–27]; however, its relatively large comb line spacing limits its suitability for high-resolution spectroscopy and hinders the detection of narrow-band gas absorption signals.

The spectral interleaving technique in comb-based spectroscopy enables spectral resolution far beyond the intrinsic comb line spacing by stepping the central frequency or adjusting the comb line interval, making broadband and high-resolution comb spectroscopy feasible. For instance, micro-resonator combs with repetition rates on the order of tens of GHz can achieve several hundredfold interleaving by tuning the cavity resonance in steps of 12.5 MHz. However, this process requires not only synchronous tuning of the pump source and the cavity resonance to maintain comb stability, but also precise temperature control to manage thermal effects. These combined requirements impose stringent demands on the control system [28]. Similarly, by adjusting the central frequency of an EOFC, the spectral resolution can be improved from 25 GHz to

100 MHz [29], but the EOFC schemes, meanwhile, are usually limited by their intrinsically narrow bandwidth; cascading multiple modulators to broaden the bandwidth substantially increases both system complexity and cost. Moreover, the resolution of dual-comb spectroscopy in the terahertz regime can be improved from 250 MHz to 2.5 MHz through interleaving spectroscopy [30]. Although dual-comb systems based on mode-locked lasers can achieve very high resolution, their interleaved measurement depend on the precise and independent locking of the repetition rates and carrier-envelope offset frequencies of the two combs, which introduces considerable technical challenges.

In this work, we proposed a high-resolution interleaved DCS technique based on an RFSL (DCS-RFSL), which simultaneously achieves the wide bandwidth and high resolution. We constructed a dual-comb structure using two RFSLs, driven by an external 16 GHz RF signal applied to a frequency-shifted modulator, generating an optical frequency comb consisting of 50 lines with a total bandwidth of 800 GHz. This comb was then compressed into the RF domain using another optical comb with a repetition rate of 15.999 5 GHz, resulting in an RF bandwidth of 25 MHz and an RF comb tooth spacing of 500 kHz. Subsequently, we proposed a novel interleaved optical frequency comb approach that required only an electro-optic modulator, an RF source, and a distributed-feedback laser (DFB), resulting in a greatly simplified architecture. We employed modulation sideband optical injection locking to stabilize a DFB to a higher-order sideband generated by an EOM driven by an RF source. By varying the RF frequency, spectral interleaving of the dual combs was achieved, inheriting the high accuracy and stability of the RF reference. During the experiment, with the single measurement time of 10 ms, the combs were interleaved 32 times at a step size of 500 MHz (4 pm), enabling the measurement of the transmission spectrum of an FBG with a bandwidth

of 641.5 GHz. Furthermore, the same system was used to measure the absorption spectrum of the  $\text{H}^{13}\text{C}^{14}\text{N}$  gas over a bandwidth of 536.5 GHz. Within the original 16 GHz comb line spacing, a 160-fold interleaving was achieved, enhancing the spectral resolution from 16 GHz to 100 MHz (0.8 pm). The measured spectrum based on the proposed approach showed excellent agreement with the reference spectrum, validating the proposed method, which offered an accessible and practical pathway to high-performance dual-comb spectroscopy.

## 2. Principle

The operating principle of the interleaved DCS-RFSL technique is illustrated in Fig. 1. A dual-RFSL structure, seeded by a common CW laser, generates two OFCs with a slight repetition rate difference. These combs exhibit flat-top spectral profiles, with line spacings of  $f_{r1}$  and  $f_{r1} + \Delta f_r$ , respectively, where  $\Delta f_r$  represents a small and precisely controlled repetition frequency detuning. Since both of them originate from the same seed laser and share identical optical paths and modulation conditions, their phase fluctuations are strongly correlated. This eliminates the need for active phase-locking electronics, which are typically required in conventional dual-comb systems to maintain the stability, thereby significantly reducing system complexity and costs.

The two combs are combined to form a dual-comb source, which then interrogates the sample. The sample's spectral response is encoded onto the combined optical field, giving rise to a multi-heterodyne beat note when detected on a single photodetector. This signal contains the interference between every pair of lines from the two combs. The temporal interferogram is captured and subsequently transformed into the RF domain via the fast Fourier transformation (FFT). In the RF spectrum, each pair of optical comb lines produces a unique beat note, resulting in an RF comb with a line spacing of  $\Delta f_r$ . The optical spectral information of the sample is thus down-converted into a

measurable RF comb. To achieve spectral interleaving and enhance resolution, the seed laser frequency is tuned in discrete steps of  $f_{r1}/N$ , where  $N$  is the number of interleaving steps. With each frequency step, the entire dual-comb spectrum is shifted accordingly. This process generates  $N$  distinct interferograms, each corresponding to a slightly offset spectral sampling position. After the Fourier transformation,  $N$  sets of RF comb spectra are obtained. These spectra are interleaved and stitched together in the optical domain, effectively

increasing the sampling density by a factor of  $N$ . As a result, the final reconstructed optical spectrum achieves the spectral resolution of  $f_{r1}/N$ , representing an  $N$ -fold improvement compared to the native resolution limited by the original optical comb line spacing,  $f_{r1}$ . This method synergistically combines the broad bandwidth and high coherence of the RFSL-generated frequency combs with the precision of a frequency-stepped seed laser, enabling high-resolution spectroscopy without the need for complex feedback stabilization.

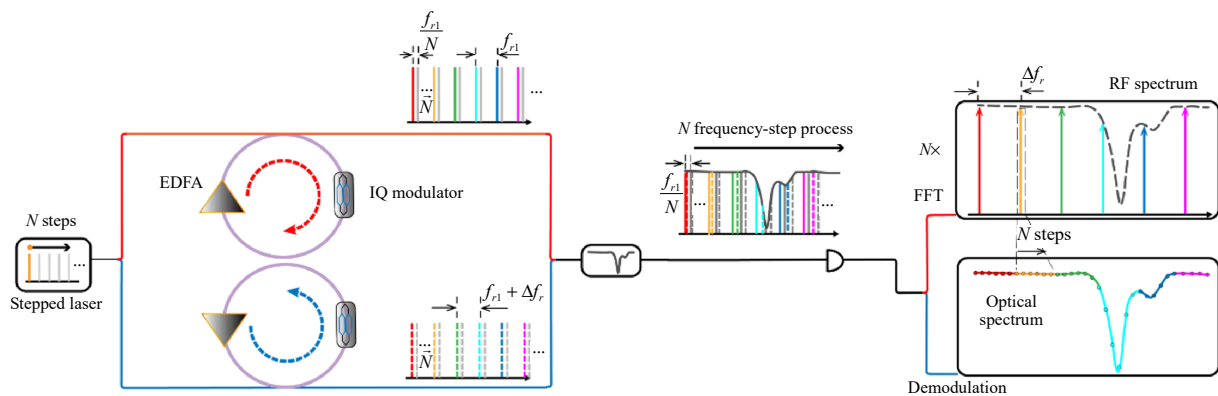


Fig. 1 Principle of the interleaved DCS-RFSL technique (EDFA: erbium-doped fiber amplifier; IQ: in-phase and quadrature).

### 3. Experimental setup

The experimental setup of the DCS-RFSL system is shown in Fig. 2. It consisted primarily of a frequency-stepping system and a dual-RFSL. Seed light with a wavelength around 1 550 nm from a CW laser was modulated by an EOM to generate multiple sidebands. The second sideband was selectively injected into the DFB laser, where it acted as a new seed laser source for the dual-RFSL. Due to the frequency-shifted injection effect, the frequency of the DFB laser followed that of the second sideband. Frequency stepping of the seed laser was achieved by controlling the frequency of the external RF signal applied to the EOM. Note that injection locking could be achieved by using a sideband of a higher order  $M$  with a proper modulation depth applied to the modulator. In this case, tuning the seed laser by one free spectral range

(FSR) required the RF to be adjusted by the  $\text{FSR}/M$ , where  $M$  is the selected sideband order. To ensure the locked reliability, the DFB bias current was continuously tuned to follow the sideband movement, and the injection-locked seed laser was monitored in real time using a delayed self-heterodyne setup to verify a stable locked state [33]. Then, the seed laser was split into two beams by a 50:50 coupler and injected into the dual-RFSL in opposite directions. Each identical RFSL was composed of a polarization controller (PC), an IQ modulator, an EDFA, an isolator, and an optical bandpass filter (BPF). The seed laser was fed into an IQ modulator, which was driven by an external RF signal and was biased at a specific voltage point to achieve single-sideband (SSB) suppression modulation, which enabled pure optical frequency shifting. The intra-loop amplifier compensated for loop losses, while the isolator prevented back

reflections. The two counter-propagating seed beams circulated continuously in the dual frequency-shifting loop, ultimately generating a broadband and flat-topped dual-comb source. The repetition rates of the dual-comb system were precisely controlled by two independently operated RF sources, set at 16 GHz and 15.999 5 GHz respectively, resulting in

a detuning of 500 kHz. The combined dual-comb output was directed into two branches: a measurement branch containing a sample and a reference branch with only one bare optical fiber. The time-domain signals from both the reference and measurement branches are simultaneously recorded by two channels of an oscilloscope (OSC).

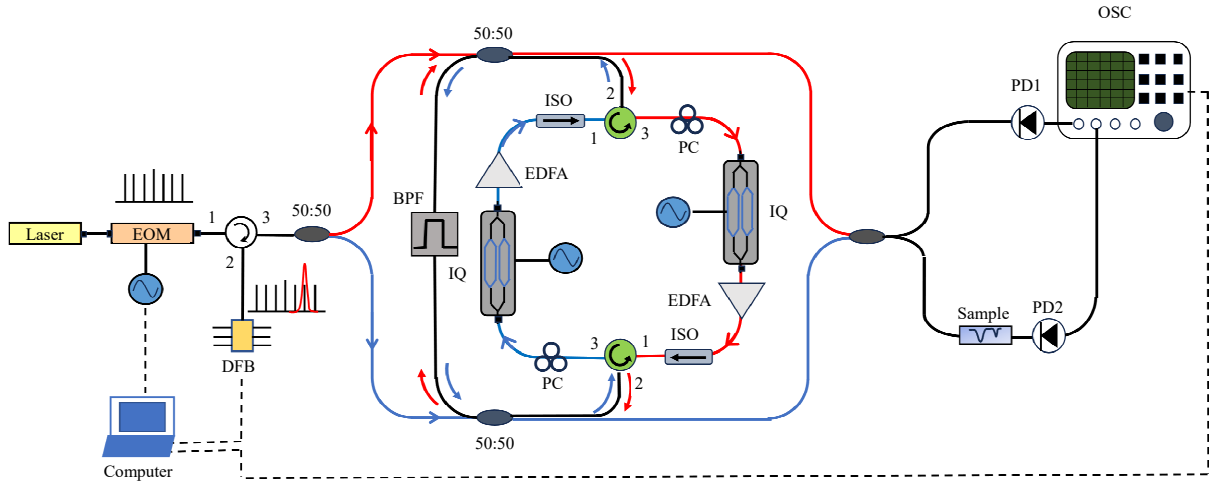


Fig. 2 Experimental setup of the proposed DCS-RFSL system (EOM: electro-optic modulator; BPF: bandpass filter; PC: polarization controller; IQ: in-phase quadrature modulator; ISO: isolator; EDFA: erbium-doped fiber amplifier; PD: photo detector).

## 4. Results

In the experiment, we employed the injection-locked DFB laser as the seed laser for the dual-RFSL. Since both combs are derived from the same seed laser via injection locking, they possess inherent mutual coherence, which eliminates the need for complex active phase-locking systems. Once the dual-comb source was generated, the combs were shifted by tuning the RF signal to the EO modulator, while the DFB laser current was adjusted concurrently to maintain a stable injection-locked state throughout the process. The entire comb can be tuned over a full FSR (16 GHz) in response to the applied RF frequency, with the tuning step size can be precisely controlled by the externally applied RF drive signal.

For a clear visual presentation, Fig. 3(a) shows the overlapped spectra of eight selected comb lines from a single optical comb tuned across one FSR, recorded with an optical spectrum analyzer (OSA) at a resolution of 0.03 nm. The results confirm a

flat-top spectral profile with a bandwidth exceeding about 5 nm. The higher comb line power at longer wavelengths is most probably due to a non-flat net gain profile within the loop, which is determined by the combined effects of the EDFA's wavelength-dependent gain and the polarization-related loss in our system. The signal-to-noise ratio (SNR) of higher-order comb lines decreases due to ASE noise accumulation. By employing a bandpass filter within the loop to limit their number, we ensure that all ~50 generated lines maintain an acceptable SNR for high-precision measurement. It is noted that the bandwidth of the RFSL-generated comb is primarily limited by the finite gain bandwidth of the optical amplifier and the ASE noise, which restricts the number of usable comb lines and degrades the SNR of higher-order lines, respectively. Employing an amplifier with the higher gain and lower noise would allow a wider bandpass filter to be used, supporting a broader optical spectrum. A zoomed-in view of the shorter-wavelength region

(1 551.05 nm–1 551.40 nm) in Fig. 3(b) shows well-defined comb lines with the SNR of 19.95 dB. The corresponding longer-wavelength region (1 554.6 nm–1 555.0 nm) in Fig. 3(c) exhibits the SNR of 16.38 dB. The amplitude stability of the generated comb is ensured by maintaining a high single-sideband suppression ratio ( $>23$  dB) in the SSB modulator, effectively suppressing multi-path interference and the associated intensity fluctuations.

This is evidenced in Figs. 3(d) and 3(e), which show the power distribution of individual comb lines during tuning, demonstrating excellent stability and outstanding flatness with fluctuations below 1.5 dB across the selected wavelength regions throughout the tuning process. Furthermore, the dual-channel measurement scheme inherently mitigates the majority of any residual common-mode intensity noise.

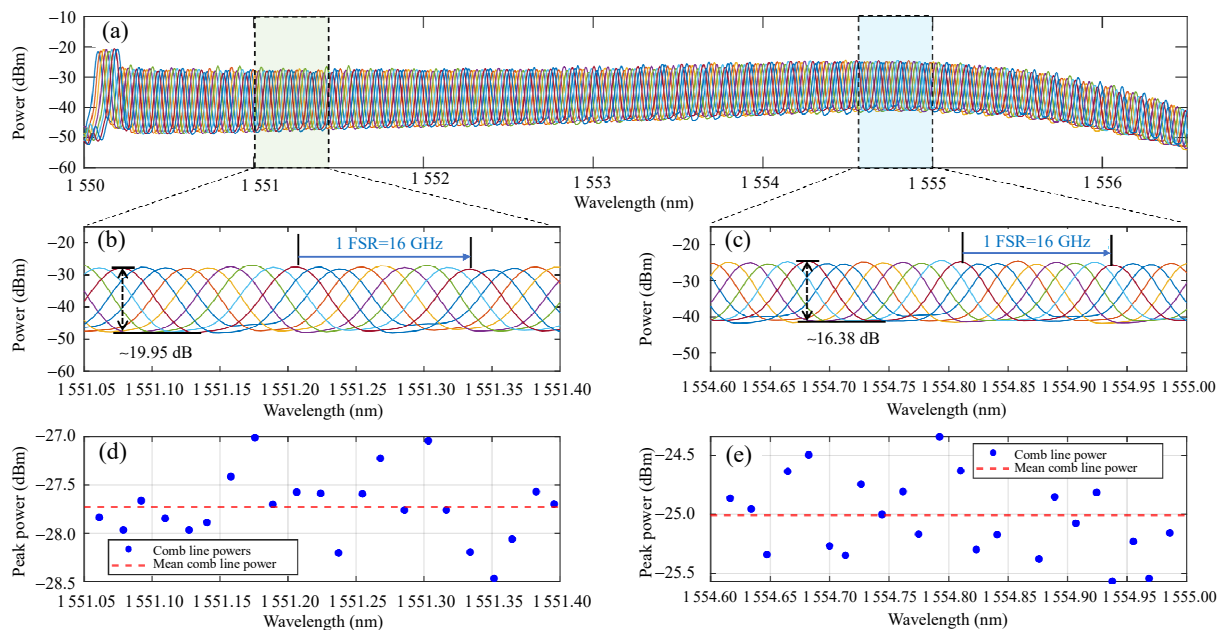


Fig. 3 Characterization of the flat-top optical frequency comb generated by the RFSL: (a) overlapped spectra of a single optical comb tuned across one free spectral range (16 GHz), showing a flat-top spectral profile spanning over 5 nm, measured with an OSA at 0.03 nm resolution, (b) zoomed-in view of the shorter-wavelength region (1 551.05 nm–1 551.40 nm), where the comb exhibits a SNR of 19.95 dB, (c) zoomed-in view of the longer-wavelength region (1 554.6 nm–1 555.0 nm), showing a reduced SNR of 16.38 dB, and (d) and (e) power distribution of individual comb lines during tuning, demonstrating stable power characteristics.

Figure 4 presents the temporal and spectral characteristics of the dual-comb interferometer. In Fig. 4(c), the time-domain interference signals are shown for both the measurement path (with the  $\text{H}^{13}\text{C}^{14}\text{N}$  gas sample) and the reference path (without the sample), recorded simultaneously over a 10-ms acquisition window (100 MS/s, 1 million points per waveform). A stable and periodic interference pattern was observed throughout the acquisition. Figure 4(a) provides a zoomed-in view of the segment highlighted in green in (a), clearly demonstrating a consistent interference period of 2  $\mu\text{s}$ , which corresponds to a repetition rate

difference of 500 kHz between the two optical frequency combs. This repetition rate difference directly defined the spacing of the resulting RF comb lines. The corresponding RF comb spectra, obtained by applying an FFT to the full 10 ms time-domain data, are displayed in Fig. 4(e). The spectrum exhibited a total of 50 well-resolved comb lines spaced by 500 kHz, spanning an RF bandwidth of 25 MHz. The shown comparison represents a single step of the interleaving process, illustrating how the RF spectra acquired with and without the sample were compared to extract spectral information. The low SNR in the single-shot

temporal interferogram was probably contributed by the relative intensity noise (RIN) and phase noise, along with other technical noise sources. However, the system's multi-cycle interference allowed the SNR to be significantly improved

in the frequency domain by coherent averaging. The 10-ms acquisition time enabled sufficient coherent averaging to yield a high-fidelity RF comb spectrum, ensuring reliable spectral retrieval.

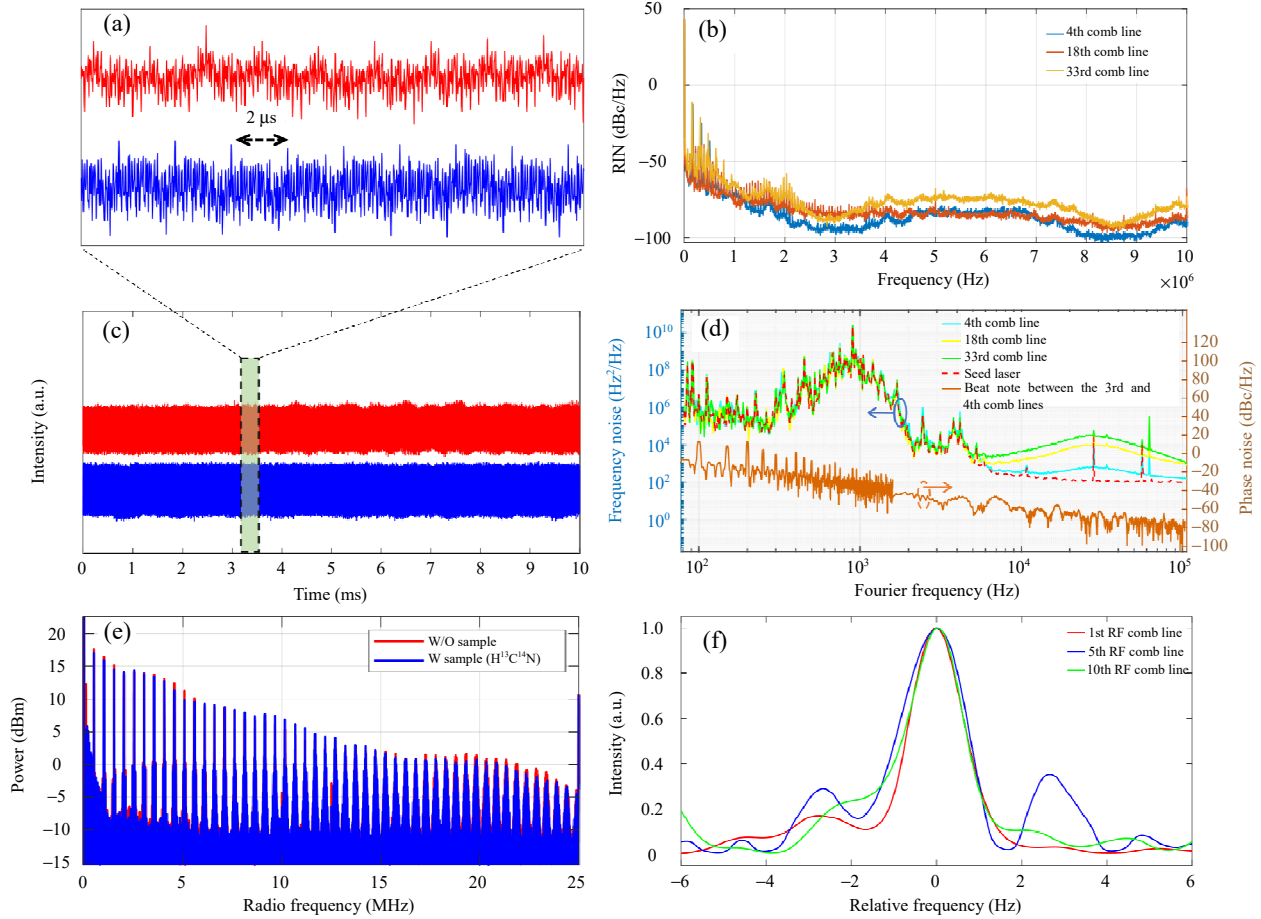


Fig. 4 Performance characterization of the dual-comb system: (a) zoomed-in view of the green-selected region in (c), and the interference period is  $2\ \mu\text{s}$ , (b) RIN of the 4th, 18th, and 33rd order comb lines, (c) temporal waveform of dual-comb interferometer recorded in 10 ms with a sampling rate of 100 MS/s, (d) frequency-noise spectra of the same three comb lines and the seed laser, and phase-noise spectrum of the beat between the 3rd and 4th order comb lines, (e) the electrical spectrum of reference branch and measurement branch containing total 50 lines (W: with; W/O: without), and (f) linewidths of individual RF comb teeth from the dual-comb heterodyne beat. Spectra of the 1st, 5th, and 10th RF comb teeth (centered near 500 kHz, 2.5 MHz, and 5 MHz, respectively) are shown. Each exhibits a 3-dB linewidth on the order of a few Hz (RBW=1 Hz).

The RIN and frequency noise of selected comb lines were experimentally characterized. As illustrated in Fig. 4(b), the RIN of the 4th, 18th, and 33rd order comb lines remain below  $-70\ \text{dBc/Hz}$  in the high-frequency range ( $>2\ \text{MHz}$ ). The dual-channel OSC measurement scheme used in this work effectively suppressed such RIN. Figure 4(d) displays the frequency noise of individual comb

lines, with a slight rise in the frequency noise noted for higher-order lines but still at an acceptable level. In addition, the phase noise of the beat note between adjacent comb lines was also measured, as shown in Fig. 4(d). The mutual coherence of the two combs was evaluated by measuring the RF beat-note linewidth between the corresponding comb teeth at different orders (1st, 5th, and 10th), as shown in

Fig. 4(f). Under a resolution bandwidth (RBW) of 1 Hz, the measured 3-dB linewidths were on the Hz level, corresponding to the coherence time of about hundreds of milliseconds. This result demonstrated that the two combs could maintain the phase stability over a time window on the order of hundreds of milliseconds.

We firstly utilized the DCS-RFSL system to characterize the transmission spectrum of an FBG. The transmission spectrum spanning 641.5 GHz was acquired in the single 10 ms measurement with 16 GHz resolution. By interleaving the combs 32 times, the spectral resolution was enhanced to 500 MHz (4 pm), as shown in Fig. 5(a). To validate the results obtained with the proposed method, we also measured the transmission spectrum of the same FBG using the scanning laser spectroscopy [31–33] to serve as a reference spectrum. Figure 5(b) shows that the deviation between the proposed DCS measurement and the reference spectrum, with the maximum discrepancy across the entire 641.5 GHz bandwidth, remained within 5%. Figure 5(c) presents zoomed-in views of these selected FBG absorption dips highlighted in the shaded region of Fig. 5(a), demonstrating almost overlap. The excellent agreement with the reference spectrum

validated the reliability of the proposed approach.

Utilizing the same experimental setup, we achieved 160-fold interleaving within the original 16 GHz comb line spacing, enhancing the spectral resolution from 16 GHz to 100 MHz (0.8 pm), and performed measurement on an  $\text{H}^{13}\text{C}^{14}\text{N}$  gas cell. The fiber-coupled gas cell had a path length of 16.5 cm under the standard pressures of 25 Torr and was maintained at approximately 24 °C. Figure 6(a) shows the absorption spectrum of  $\text{H}^{13}\text{C}^{14}\text{N}$  over a bandwidth of 536.5 GHz, centered at an emission wavelength of 1 550.08 nm. The spectrum included absorption lines corresponding to transitions P11–P16 in the  $2\nu_3$  band. For reference, the absorption of the gas cell was also measured using scanning laser spectroscopy. Figure 6(b) presents the relative deviation between the comb-based measurement and the reference spectrum over the entire bandwidth. Most residual errors were below 5%, although the deviation increased toward the end of the band. This was attributed to the accumulation of the ASE noise during the generation of the dual-comb resource in the RFSL, which reduced the SNR of the comb lines. Zoomed-in views of the absorption lines in the shaded regions (Region I, Region II, and Region III) are presented in Fig. 6(c).

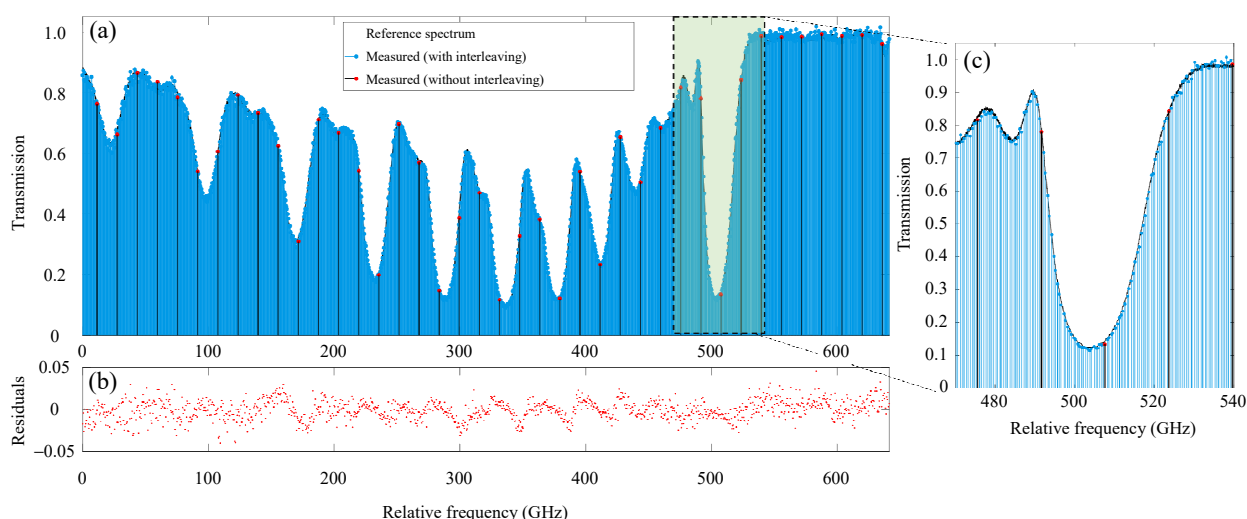


Fig. 5 Measured FBG transmission spectra and corresponding error analyses: (a) the transmission spectrum of the FBG: the comb line spacing before interleaving is 16 GHz (black lines); after interleaving, the resolution is improved to 500 MHz (blue lines); an additional reference spectrum of the FBG measured using scanning laser spectroscopy is included (the black curve), (b) the relative error between the measurement results and the reference spectrum, and (c) the zoomed-in view of the deepest absorption peak centered at a relative frequency of 504 GHz.

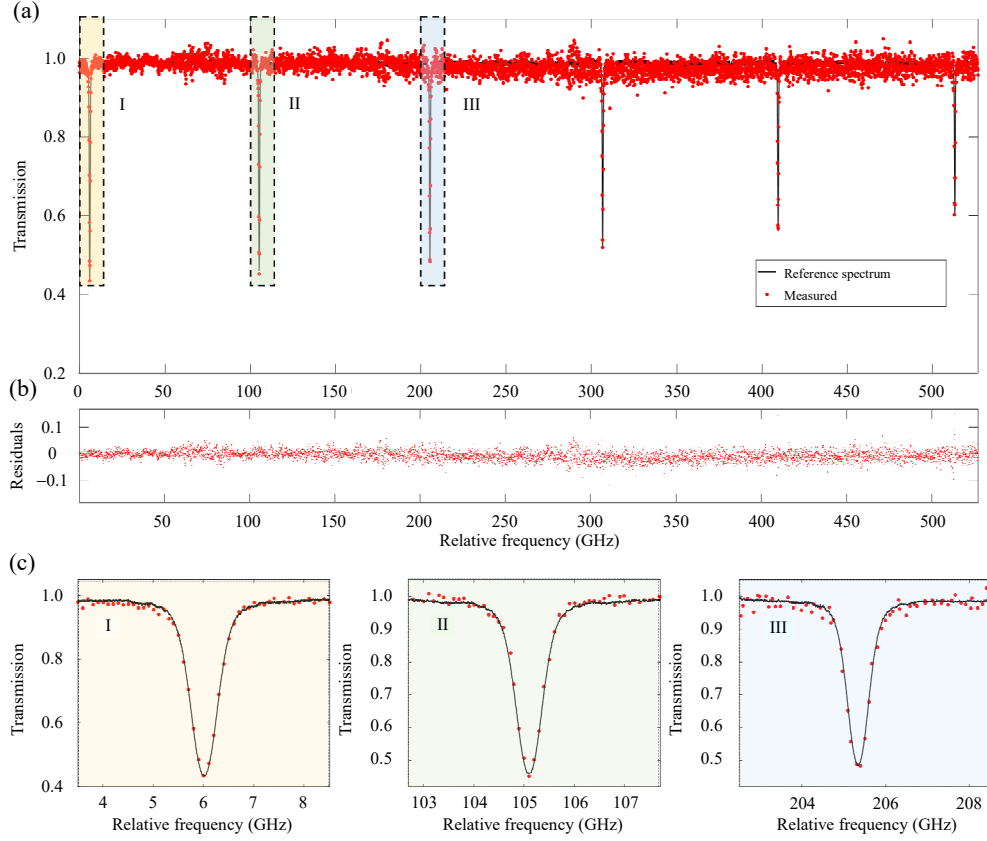


Fig. 6 Measured  $\text{H}^{13}\text{C}^{14}\text{N}$  gas transmission spectra and corresponding error analyses: (a) the transmission spectrum of the P11–P16 absorption lines of  $\text{H}^{13}\text{C}^{14}\text{N}$ , measured with the single acquisition time of 10 ms and resolution of 100 MHz, (b) the relative residuals between the measurement results and the reference spectrum, and (c) zoomed-in view of the three selected absorption lines.

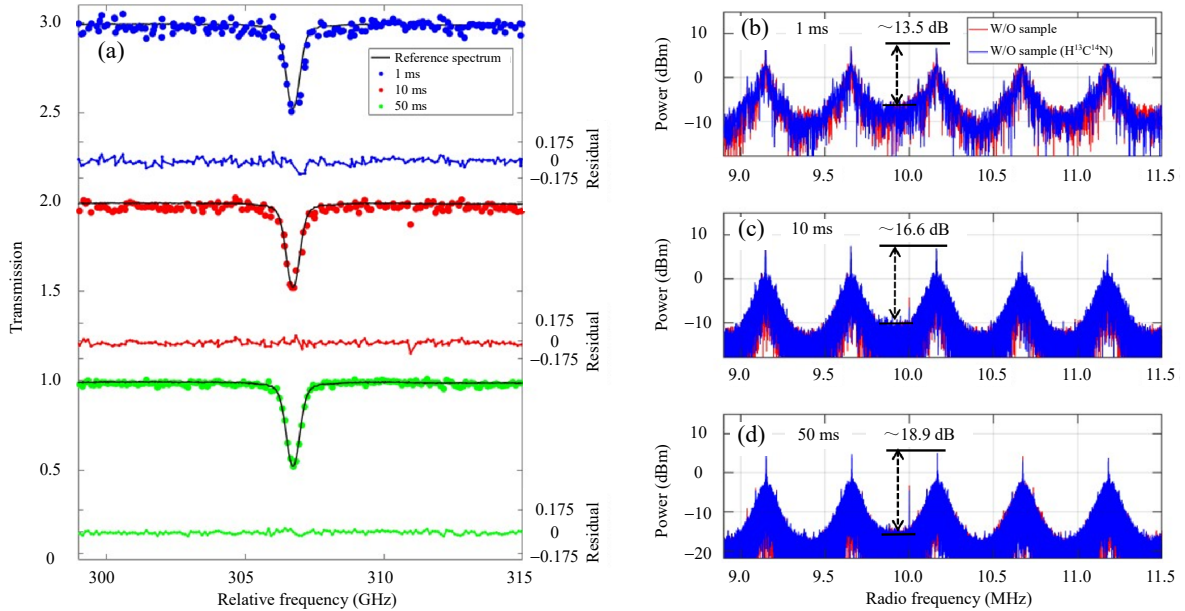


Fig. 7 Spectral measurement and the RF comb SNR evolution with acquisition time: (a) measured transmission (points) and a reference spectrum (the solid line) of the P14 absorption line in the  $\text{H}^{13}\text{C}^{14}\text{N}$  gas at 1 ms (blue), 10 ms (red), and 50 ms (green) acquisition time; and residuals are also shown as the offsets below. (b)–(d) Selected beat notes of the corresponding RF beat spectrum (near 10 MHz) under (b) 1 ms, (c) 10 ms, and (d) 50 ms acquisition time, with the absorbing sample (blue) and without (red, the reference). The SNR increases from 13.5 dB at 1 ms, to 16.6 dB at 10 ms, and to 18.9 dB at 50 ms, demonstrating the effect of coherent averaging.

The SNR of the comb can be improved by acquiring data over longer single-measurement durations, thereby enhancing spectral measurement fidelity. Accordingly, interleaved dual-comb spectroscopy was performed with acquisition time of 1 ms, 10 ms, and 50 ms. The results, focused on the P14 absorption line, are summarized in Fig. 7. Figure 7(a) shows the measured transmission spectra alongside a fitted reference and the corresponding residuals, illustrating the impact of acquisition time on spectral retrieval accuracy. Figures 7(b)–7(d) present the corresponding RF comb spectra, presenting selected beat notes near 10 MHz. The SNR of a representative comb line increased systematically from approximately 13.5 dB at 1 ms, to 16.6 dB at 10 ms, and to 18.9 dB at 50 ms.

## 5. Discussion and conclusions

In summary, we have proposed and demonstrated an interleaved dual-comb spectroscopy technique based on a dual recirculating frequency-shifting loop. By injecting a CW into a dual-RFSL, we generated a flat-topped dual-comb source spanning over 5 nm. Using the optical injection locking technique, we constructed a seed laser frequency tuning system that inherited the high precision of the RF reference frequency, while the flat-topped comb exhibited excellent power stability throughout the tuning process. We demonstrated the detection of both an FBG (with 500 MHz resolution) and the  $\text{H}^{13}\text{C}^{14}\text{N}$  gas (with 100 MHz resolution) by employing different interleaving schemes, which confirmed the flexibility and reliability of the system. The demonstrated 100 MHz resolution did not represent the system's ultimate limit, as the higher resolution (e.g., 10 MHz) could be achieved by further increasing the interleaving density. The ultimate resolution limit in our system was most probably determined by the frequency stability of the seed laser.

The dual-comb system presented here addressed several limitations of existing methods. Unlike the

mode-locked laser based dual-comb systems, our approach generated two combs from a single seed laser in an RFSL, removing the need for complex active phase-locking electronics. Conventional EOFC systems can also share a seed laser and avoid phase locking, but they usually have a narrow bandwidth. Our RFSL-based comb delivered a broad, flat-top optical bandwidth, ensuring uniform sensitivity over a wide spectral range that is essential for high-fidelity broadband spectroscopy. Microresonator combs may reach wide bandwidths, yet their interleaving often requires simultaneous tuning of the pump and cavity resonance, which complicates the operation. In our work, we employed laser scanning spectroscopy as a reference technique. It provided wide tuning, high resolution, and high speed, but required a continuously tunable laser covering a large spectral span, which came at a substantial cost and made widespread application impractical. By integrating the advantages of the seed-sharing and phase-lock-free operation, while delivering the broad and uniform bandwidth and flexible spectral interleaving, our system avoided the above trade-offs. Built from low-cost components and operating in a simple and reliable manner, it enabled simultaneously high-resolution, broadband, and cost-effective spectrometric measurement, making it highly attractive for gas sensing and environmental monitoring applications.

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## Declarations

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**Use of AI Statement** None.

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