

Reconfigurable single shot spectroscopy reaching 86 femtometers resolution

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This manuscript proposes a reconfigurable single-shot spectroscopic method, achieving a record 86-femtometer resolution and demonstrating its power by capturing rapid spectral dynamics in fiber gratings, thereby significantly broadening its application potential. The manuscript requires substantial enhancement in its content and depth to meet the high standards of Nature Communications. Several key aspects need to be addressed to strengthen the study's impact and suitability for the journal.

1. The high-precision spectroscopic systems based on programmable dispersers or tunable optical filters have been reported previously. Thus, the novelty of this method needs to be emphasized in the manuscript and the superiority is suggested as well.

2. The term "reconfigurable single-shot spectroscopy" might appear conceptually ambiguous. While "single-shot" implies that each measurement is performed within a single acquisition event, "reconfigurable" usually refers to switching among different configurations, potentially involving multiple measurements. It would be helpful if the authors could clarify whether the reconfiguration occurs between successive single-shot measurements or within a single measurement sequence.

3. In Figure 2(h–i), the manuscript states that "the resolution is improved to 25.6 pm / 6.2 pm by adding more dispersion," but the corresponding dispersion values are not specified.

4. Section 4.5 introduces a theoretical constraint linking the key figures of merit, e.g., bandwidth, resolution, and acquisition time, through dispersion. However, the manuscript does not explicitly show how this theoretical relation maps onto the experimental observations.

It would considerably strengthen the paper if the authors could provide two complementary mappings:

(1) a theoretical mapping illustrating how the limiting resolution is expected to scale with dispersion based on Eq. 6 and the underlying assumptions, and

(2) an experimental mapping showing measured resolution as a function of actual dispersion (or loop circulation number N).

Comparing these two mappings would directly validate the constraint model proposed in Section 4.5 and clarify whether the experimentally observed 86 fm resolution approaches the theoretical limit or remains below it due to system-level imperfections.

5. The manuscript claims a record-breaking resolution of 86 femtometers, which is indeed impressive. However, the comparison with other state-of-the-art single-shot or reconfigurable spectroscopy systems (e.g., VIPA-based or microcavity-comb approaches) could be more quantitative.

Reviewer #2

(Remarks to the Author)

This manuscript reports a reconfigurable single-shot spectroscopic system based on a time-stretch architecture. By integrating a pulse picker, a programmable dispersion loop, and a tunable optical filter, the authors claim to achieve fully programmable control of spectral bandwidth, resolution, and acquisition rate, reaching a spectral resolution of 86 femtometers at 1.5 μm . The experimental setup is carefully engineered, and the introduction of “programmable dispersion” into a time-stretch framework is technically appealing and demonstrates a notable degree of engineering innovation. However, while the experimental work is solid, several conceptual and contextual issues require clarification before the scientific impact of the manuscript can be properly evaluated:

1. The authors mainly compare their system with Fourier-transform infrared (FTIR) spectrometers; however, FTIR does not fully represent the current state of the art in single-shot or ultrafast spectroscopy. The statement “No other technique achieves this level of single-shot resolution” also appears overstated. How does the system compare with recent dual-comb or electro-optic comb spectroscopy methods, and does its resolution differ by orders of magnitude from other time-stretch-based spectroscopic approaches?
2. The manuscript claims to “overcome” the trade-off between bandwidth, resolution, and acquisition speed, yet the results indicate resolution is improved by sacrificing speed. Does the system truly resolve this limitation, or merely allow switching between different trade-off regimes?
3. Since the current PS-FBG/PZT test remains a static or quasi-periodic case. Could the authors demonstrate or discuss whether the system can perform transient absorption spectroscopy or equivalent single-shot transient measurements, which would better substantiate its claimed advantage for ultrafast dynamics?
4. The setup includes multiple AOMs, MEMS switches, EDFAs, and long DCF fibers, making it complex and environmentally sensitive. How might these challenges be addressed for integration or real-world use?
5. The “fully programmable” claim remains qualitative. Could the authors provide a quantitative model or numerical analysis that more clearly demonstrates how programmability enables simultaneous adjustment of bandwidth, resolution, and acquisition rate?

Reviewer #3

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

All my previous concerns have been adequately addressed. I recommend this paper for publication.

Reviewer #2

(Remarks to the Author)

I am content with the revisions.

Reviewer #3

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

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Response to Reviewers

Manuscript Title: Reconfigurable single-shot spectroscopy reaching 86 femtometers resolution

Dear Reviewers,

We sincerely thank the Reviewers for their careful evaluation of our manuscript and for the constructive and insightful comments. We appreciate the opportunity to revise our manuscript and believe that the revisions have significantly improved the clarity, depth, and impact of the work. Below, we provide a point-by-point response to all comments. Reviewer comments are reproduced in italics, followed by our responses. All changes have been highlighted in the revised manuscript, with page and, Line numbers indicated where appropriate.

Response to Reviewer #1

General comment:

We thank the reviewer for recognizing the potential impact of our work, particularly the record spectral resolution and the ability to capture rapid spectral dynamics. We agree that additional depth and clarification are required to meet the high standards of Nature Communications. Accordingly, we have substantially revised the manuscript to strengthen the discussion of novelty, clarify key concepts, and provide explicit theoretical-experimental validation.

1. The high-precision spectroscopic systems based on programmable dispersers or tunable optical filters have been reported previously. Thus, the novelty of this method need to be emphasized in the manuscript and the superiority is suggested as well.

Response: We thank you for this important comment. We agree that programmable dispersers [1] and tunable optical filters [2] have enabled high-precision spectroscopic systems with demonstrated effectiveness in prior work. However, these approaches inherently rely on sequential spectral scanning to reconstruct a full spectrum and therefore do not constitute true single-shot spectroscopy in the operational sense. For example, acousto-optic programmable dispersive filter-based implementations are typically used in delay-scan configurations, while tunable optical filter-based systems require stepwise wavelength tuning to cover the spectral range. In both cases, the full spectrum is obtained through multiple acquisition steps, fundamentally limiting their applicability to non-repetitive or rapidly evolving spectral dynamics.

In contrast, the system proposed acquires complete spectral information within a single measurement event, without any spectral scanning or sequential tuning. More importantly,

the key novelty of this work is not limited to single-shot operation but lies in the introduction of a reconfigurable spectrometer framework that enables programmable control of spectral resolution, bandwidth, and acquisition rate within a unified platform. These parameters are intrinsically coupled and constrained by fundamental trade-offs in almost all spectroscopic systems. Rather than attempting to overcome this limitation, our approach provides a systematic and physically grounded method to navigate the trade-off space through programmable configurations. This capability allows the system to access more scenarios and extreme performance regimes that are not attainable in existing single-shot spectroscopic approaches, which typically operate at a fixed or narrowly defined working point.

To make this distinction more explicit, we have revised the manuscript accordingly. Specifically, we have

- (1) added a timing diagram (Fig. 3) to illustrate the programmable control mechanism,
- (2) included a table in Fig.3 summarizing representative operating points with quantitatively specified bandwidth, resolution, and acquisition rate
- (3) expanded the discussion to more clearly differentiate our approach from scanning-based methods and highlight its reconfigurable single-shot capability (paragraph one in introduction). By using this framework, we experimentally achieve a spectral resolution of 86 femtometers at 1.5 μm under single-shot operation, representing one of the highest spectral resolutions reported for reconfigurable single-shot spectroscopic systems, together with demonstrated operation across multiple distinct performance regimes.

[1] de La Paz J A, Bonvalet A, Joffre M. Frequency-domain two-dimensional infrared spectroscopy using an acousto-optic programmable dispersive filter[J]. Optics Express, 2019, 27(4): 4140-4146.

[2] Gat N. Imaging spectroscopy using tunable filters: a review[J]. Wavelet Applications VII, 2000, 4056: 50-64.

No.	Modification
1	Position: Page 7, Fig.3 Change: We reorganized the, Figures and added, Fig3. (a-c) to illustrate the programmable control mechanism, and, Fig3. (d) to summarize representative operating points.

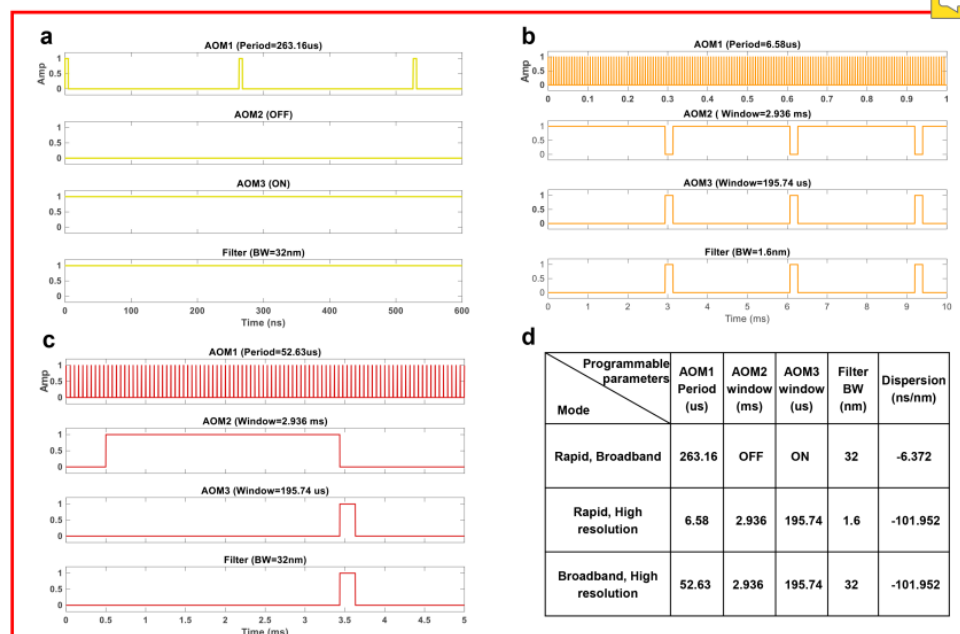


Fig. 3 Programmable operation of the system. (a–c) Timing diagrams illustrating three representative operating modes: broadband high resolution, rapid broadband, and rapid high resolution. The coordinated control of AOM1 (pulse picking), AOM2 (loop gating), and AOM3 (temporal window) enables dynamic adjustment of acquisition rate, total dispersion, and temporal stretching, which determines spectral resolution, bandwidth, and acquisition speed. (d) Summary of the programmable control parameters and corresponding performance metrics for the three modes. Each mode represents a distinct operating point within the resolution–bandwidth–acquisition-rate trade-off space. (e)

- 2 Position: Page 7, Line 1
Change: We modified the manuscript by adding a quantitative description of the programmability, including a control diagram (Fig. 3) and representative operating modes, to explicitly map programmable system parameters to bandwidth, resolution, and acquisition rate within the trade-off space.
- 1 Considering the constraint relationship described, only two of the figures of merit
2 (FOMs) can be optimized in a single setup, necessitating the sacrifice of the third. To
3 quantitatively illustrate the programmability of the proposed spectroscopy, we define
4 a set of representative operating modes based on coordinated control of system param-
5 eters. As shown in Fig. 3, programmability is realized through synchronized temporal
6 gating operations that jointly determine the acquisition rate, total dispersion, and
- 3 Position: Page 8, Line 1
Change: We modified the manuscript by adding a quantitative description of the programmability, including a control diagram (Fig. 3) and representative operating modes, to explicitly map programmable system parameters to bandwidth, resolution, and acquisition rate within the trade-off space.

	1 effective temporal window of the optical filter, which in turn define the measurement 2 speed, spectral resolution, and bandwidth within the trade-off space described by 3 Eq.(5) and Eq.(6). Specifically, this control is implemented through pulse picking to 4 set the acquisition rate, loop gating to control the effective dispersion via the number 5 of circulations and round-trip delay, and temporal windowing to match the stretched 6 pulse duration and filtering process, as illustrated by the representative timing con- 7 figurations in Fig. 3(a–c). Based on this framework, three representative operating 8 modes, broadband high resolution, rapid broadband, and rapid high resolution are 9 defined, each corresponding to a distinct operating point implemented through a 10 specific combination of programmable control parameters, as summarized in Fig. 3(d).
4	Position: Page 2, Line 2 Change: We reorganized the introduction and added the following discussion about distinction between single-shot and multi-shot spectroscopy include optical filter- based method. 2 Beyond traditional Michelson-based Fourier transform spectroscopy (MFTS), sub- 3 stantial efforts have been devoted to the development of advanced spectroscopic 4 approaches, including dual-comb frequency comb spectroscopy (DFCS) [1], electro- 5 optic comb spectroscopy [2], tunable optical filter spectroscopy [3] microresonator- 6 based comb spectroscopy [4], and integrated reconstructive spectroscopy based on 7 Mach–Zehnder interferometer chips [5]. The latter two approaches provide compact 8 and integrated solutions, and filter-based spectroscopies are relatively easy to imple- 9 ment, whereas the former comb-based spectroscopies offer superior performance, 10 achieving spectral resolutions down to the kilohertz–megahertz regime. However, these 11 approaches are fundamentally constrained by intrinsic trade-offs among spectral res- 12 olution, bandwidth, and acquisition rate [6], where achieving ultrahigh resolution 13 typically comes at the expense of limited spectral bandwidth. More importantly, all 14 these approaches rely on heterodyne detection, in which optical spectra are mapped 15 to the radio frequency (RF) domain and reconstructed through electrical signal pro- 16 cessing. In practice, they require temporal averaging or scanning in RF domain to 17 ensure sufficient signal to noise ratio. These characteristics prevent them from consti- 18 tuting single-shot spectroscopy, where a complete spectrum is acquired within a single 19 measurement event.

2. The term "reconfigurable single-shot spectroscopy" might appear conceptually ambiguous. While "single-shot" implies that each measurement is performed within a single acquisition event, "reconfigurable" usually refers to switching among different configurations, potentially involving multiple measurements. It would be helpful if the authors could clarify whether the reconfiguration occurs between successive single-shot measurements or within a single measurement sequence.

Response: We thank you for pointing out this important conceptual ambiguity. In our work, "single-shot" refers to the acquisition of a complete spectrum from a single optical pulse, without any spectral scanning or averaging. The effective measurement time is therefore determined by the pulse duration, which can reach the femtosecond regime. The

reconfiguration in our system occurs between successive single-shot measurements, rather than within a single pulse. Specifically, the system parameters (e.g., dispersion, bandwidth, and acquisition rate) can be reprogrammed on a millisecond timescale, enabling rapid switching of measurement configurations. As a result, each individual pulse can be measured under a user-defined configuration, allowing flexible adaptation to different measurement scenarios or performance requirements. So, each measurement remains a single-shot acquisition, with the reconfigurability enabling programmable control of measurement conditions across successive pulses. We have clarified this definition and the operational sequence in the revised manuscript to avoid ambiguity.

No.	Modification
1	Position: Page 3, Line 8 Change: We reorganized the Introduction to clarify the definition of “single-shot” spectroscopy and to explicitly describe the operational sequence of the reconfigurable scheme, emphasizing that the reconfiguration is performed between successive single-shot measurements. 4 In this work, we present a solution to the challenge of balancing spectral 5 bandwidth, resolution, and acquisition speed in single-shot spectroscopy. Our recon- 6 figurable architecture integrates a tunable optical filter, a dispersion-programmable 7 loop with amplification, and a pulse picker, enabling coordinated and programmable 8 control of key system parameters. <u>The proposed system enables single-shot spec-</u> 9 <u>tral acquisition with programmable control of spectral resolution, bandwidth, and</u> 10 <u>acquisition rate. The reconfigurability is implemented between successive single-shot</u> 11 <u>measurements, allowing each pulse to be measured under a distinct, user-defined sys-</u> 12 <u>tem configuration. This approach facilitates a significant enhancement in spectral</u> 13 <u>resolution by increasing dispersion at the cost of bandwidth or acquisition speed.</u>
2	Position: Page 11, Line 26 Change: We added a description of 'single-shot' spectroscopy, emphasizing that reconfiguration is performed between successive single-shot measurements. 25 This work introduces a pioneering approach to achieve rapidly reconfigurable single- 26 shot spectroscopy based on the time-stretch technique. <u>Unlike sequential scanning</u> 27 <u>methods, the proposed architecture enables true single-shot acquisition with reconfig-</u> 28 <u>urable operation across different performance regimes.</u> Our system integrates a pulse

3. In, Figure 2(h–i), the manuscript states that “the resolution is improved to 25.6 pm / 6.2 pm by adding more dispersion,” but the corresponding dispersion values are not specified.

Response: We thank you for pointing out this lack of clarity. We would like to clarify that the dispersion values in, Fig. 2 are identical within each column. Specifically, the configurations in, Fig. 2(a), (d), and (g) share the same dispersion (-637.2 ps/nm), while, Fig. 2(b), (e), and (h) correspond to another dispersion value (-6.372 ns/nm), and, Fig. 2(c), (f), and (i)

correspond to a higher dispersion level (-25.49 ns/nm). In the original manuscript, the dispersion values were only explicitly indicated for, Fig. 2(a–f), and the corresponding values for, Fig. 2(g–i) were not separately stated, as they follow the same column-wise configuration. We agree that this may require the reader to infer the values, which is not sufficiently clear. To improve clarity, we have now explicitly added the corresponding dispersion values for, Fig. 2(g–i) in the, Figure caption in the revised manuscript, so that the relationship between dispersion and resolution can be directly understood without ambiguity.

Modification
Position: Page 6, Fig.2 Change: We revised the, Figure caption of, Fig. 2 to explicitly include the dispersion values for, Fig. 2(g–i), so that the corresponding measurement conditions can be clearly identified. Fig. 2 Reconfigurability results of the proposed single-shot spectroscopy across various resolutions and refresh rates using a commercial flat-top comb optical filter with a 0.8 nm free spectral range (FSR) and a 60 ps 3-dB bandwidth for each comb line. Top row: Time-domain waveforms recorded by the OSC, illustrating the refresh rate. Middle row: Reconstructed spectra for five consecutive optical pulses. Bottom row: Zoomed-in spectra comparing the OSA and OSC results. The black lines in (a), (d) and (g) represent continuously measured spectra at a rate of 380 kHz, with the repetition rate divided by 100. In the program disperser module, only DCF1 (with a dispersion of -318.6 ps/nm) is used, with two turns, resulting in a total dispersion of -637.2 ps/nm. The blue lines in (c), (e) and (h) correspond to continuously measured spectra at a rate of 152 kHz, with the repetition rate divided by 250. DCFs 1 to 4 have dispersions of -318.6 ps/nm, -1274.4 ps/nm, -1593 ps/nm, and -3186 ps/nm, respectively. All DCFs are used, with one turn each in the loop, yielding a total dispersion of -6.372 ns/nm. The red lines in (e),(f) and (i) represent continuously measured spectra at a rate of 25.3 kHz. Using the same DCFs and four turns ($N=4$) in the loop, the total dispersion is -25.49 ns/nm. Optical envelopes were estimated and digitally canceled. Spectrum data are normalized. All measurements shown are unaveraged, single-shot data.

4. Section 4.5 introduces a theoretical constraint linking the key, Figures of merit, e.g., bandwidth, resolution, and acquisition time, through dispersion. However, the manuscript does not explicitly show how this theoretical relation maps onto the experimental observations.

It would considerably strengthen the paper if the authors could provide two complementary mappings:

- (1) a theoretical mapping illustrating how the limiting resolution is expected to scale with dispersion based on Eq. 6 and the underlying assumptions, and
- (2) an experimental mapping showing measured resolution as a function of actual dispersion (or loop circulation number N).

Comparing these two mappings would directly validate the constraint model proposed in Section 4.5 and clarify whether the experimentally observed 86 fm resolution approaches the theoretical limit or remains below it due to system-level imperfections.

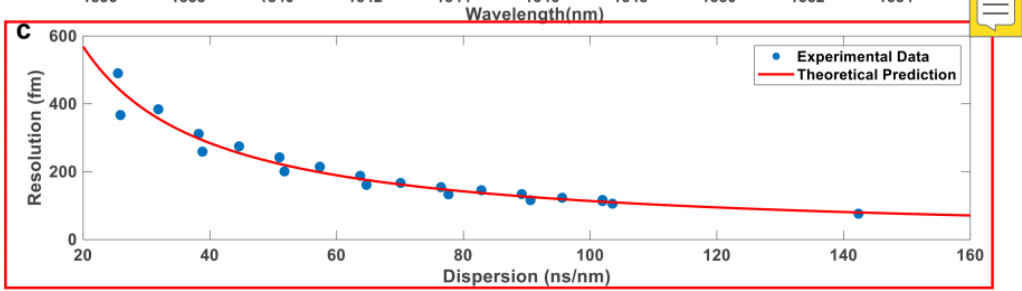
Response: We thank you for this insightful and constructive suggestion. We agree that explicitly linking the theoretical model to the experimental observations would further strengthen the manuscript. Equation (6) ($B(\Delta\lambda \times F_s)^{-1} + T_{rise} < \Delta t_2$) describes the fundamental constraint among spectral resolution, bandwidth, and acquisition rate, arising from the requirement to avoid temporal overlap of stretched pulses, while Eq. (5) ($\Delta\lambda = (N \times D \times F_s)^{-1}$) defines the dependence of spectral resolution on dispersion under the system detection conditions. More specifically, Eq. (5) shows that the spectral resolution is inversely proportional to the total dispersion when the temporal sampling resolution, determined by the oscilloscope sampling rate, is fixed. Under this condition, increasing dispersion leads to a proportional stretching of the spectral features in time, thereby improving the resolvable spectral resolution.

Following your suggestion, we have added a quantitative mapping between spectral resolution and dispersion in the revised manuscript (Fig.4 (c)). Specifically, the theoretical prediction based on Eq. (5) is plotted as a continuous curve, together with experimentally measured data points obtained at different dispersion values. The comparison shows good agreement between theory and experiment, validating the proposed model and its underlying assumptions.

Furthermore, we provide a quantitative estimate to relate the experimentally achieved resolution to the constraint described by Eq. (6). For the demonstrated operating point (

$D = -145.76$ ns/nm, bandwidth = 1.6 nm), the stretched pulse duration is approximately 233.2 ns. Taking the 10 ns AOM rise time as a conservative guard interval yields a maximum repetition rate of ~4.11 MHz under the no-overlap condition, which is close to the experimentally used value of 3.8 MHz. This shows that the achieved 86 fm resolution not only follows the theoretical scaling in Eq. (5) but also operates near the practical limit imposed by Eq. (6). In addition, under a fixed sampling rate, the inverse dependence described by Eq. (5) implies a progressively decreasing slope at larger dispersion, meaning that further increasing dispersion yields diminishing improvement in resolution while incurring increasingly severe penalties in acquisition rate and bandwidth. We have added the corresponding mapping and discussion in the revised manuscript.

No.	Modification
1	Position: Page 15, Line 5 Change: We add this discussion to explain the relation between resolution and dispersion.

	where F_s denotes the sampling rate of the oscilloscope. Eq.(5) implies that increasing either the dispersion or the oscilloscope sampling rate improves the spectral resolution. This inverse dependence holds under a fixed temporal sampling resolution determined by the oscilloscope. Under this condition, increasing dispersion maps spectral features into a longer temporal waveform, thereby improving the achievable spectral resolution. By combining Eq.(4) and Eq.(5), the following constraint on resolution and bandwidth is obtained:
2	Position: Page 9, Line 2 Change: We add this discussion to explain, Fig4 we added. each absorption peak is shown in Fig. 4(b), further demonstrating the system's capabilities. To validate the theoretical relationship described by Eq.(5), we plot the spectral resolution as a function of total dispersion, as shown in Fig. 4 (c). The solid curve represents the theoretical prediction based on Eq.(5), while the discrete points correspond to experimentally measured resolutions at different dispersion values. The experimental results show good agreement with the theoretical trend, confirming the validity of the model. The inverse dependence implies a progressively decreasing slope at larger dispersion, indicating diminishing improvement in resolution as dispersion increases.
3	Position: Page 9, Fig.4 Change: We have included a plot showing the quantitative mapping between spectral resolution and dispersion.  Fig. 4 (a) Spectra of the PS-FBG for different values of N ($N = 4, 8, 11$), where the loop dispersion is set to 12.941 ns/nm. A resolution of 86 fm (dark blue line) is achieved by adding a dispersion value of -145.76 ns/nm, while N equals 11. (b) Spectra of hydrogen cyanide gas cells measured with $N = 8$. (c) Spectral resolution as a function of total dispersion. The solid curve represents the theoretical prediction based on Eq.(5), while the markers show experimentally measured values.
4	Position: Page 8, Line 35 Change: We added this discussion to prove 86 fm resolution approaches the theoretical limit.

35	12.941 ns/nm. The stretch process can be seen. The dark blue line in Fig. 4(a) shows
36	the spectrum of the PS-FBG with a dispersion of -145.76 ns/nm. Due to the substan-
37	tial dispersion, a resolution of 86 fm (10 MHz level) is achieved, which is comparable to
38	the current state-of-the-art in MFTS systems. Considering the bandwidth of 1.6 nm,
39	the stretched pulse duration is approximately 233.2 ns. Including the 10 ns AOM rise
40	time as a guard interval yields a maximum repetition rate of approximately 4.11 MHz
41	under the no-overlap condition described by Eq.(6), which is close to the experimen-
42	tally used value of 3.8 MHz. This indicates that the achieved 86 fm resolution operates
43	near the practical limit imposed by the bandwidth–resolution–acquisition-rate trade-
44	off. Additionally, a measurement with a gas cell sample with a 5 pm bandwidth for

5. The manuscript claims a record-breaking resolution of 86 femtometers, which is indeed impressive. However, the comparison with other state-of-the-art single-shot or reconfigurable spectroscopy systems (e.g., VIPA-based or microcavity-comb approaches) could be more quantitative.

Response: We thank you for this important and insightful comment. To provide a more quantitative comparison with state-of-the-art spectroscopic techniques, we have revised the manuscript to include systematic benchmarking of representative approaches. Specifically, we have added a comparison table (Table 1) and corresponding discussion in Introduction paragraph 2, where the spectral resolution, operational principles, and measurement modalities of different spectrometers are summarized.

As presented in Table 1, conventional spatial based single-shot spectrometers, including diffraction grating, VIPA, and arrayed waveguide grating, are typically limited to picometer-level resolution due to the finite optical path difference constrained by device size or aperture. Time-stretch spectroscopies overcome this spatial limitation but remain fundamentally constrained by the intrinsic trade-off among spectral resolution, bandwidth, and acquisition rate. In contrast, other high-resolution approaches, such as micro resonator-based comb spectroscopy and Mach–Zehnder interferometer based chip scale spectroscopy, rely on spectral tuning or computational reconstruction rather than single-shot acquisition.

Based on this quantitative comparison, we have clarified in the revised manuscript that the key advance of this work lies in a reconfigurable time-stretch spectrometer framework that enables programmable control of dispersion, acquisition speed as well as optical bandwidth. This capability allows operation near the extreme limit of the resolution, bandwidth and speed trade-off space while preserving single shot acquisition. As a result, the proposed system achieves a spectral resolution of 86 femtometers under single-shot operation, representing one of the highest resolutions reported for single-shot spectroscopy, as highlighted in Table 1.

We have reorganized the introduction and added discussion on resolution of different approaches, as well as the table 1 in the revised manuscript.

Table 1 Comparison of high resolution single shot spectroscopic techniques

Reference	Technique	Readout type	Spectral resolution	Year	Key limitation
[1]	Diffraction grating	Spatial	2.4 pm	2017	Optical path difference
[2]	VIPA	Spatial	4.5 pm	2024	Etalon's finesse
[3]	Array waveguided grating	Spatial	100 pm	2022	Optical path difference
[4]	Bidirectional time-stretch	Time	2.2pm	2007	Time domain overlap
[5]	Resonator-based time-stretch	Time	24 pm	2017	Time domain overlap
[6]	Up conversion time-stretch	Time	1 pm	2023	Time domain overlap
This work	This work	Time	86 fm	2026	——

No.	Modification
1	Position: Page 2, Line 26 Change: We modified the introduction by adding a quantitative comparison with state-of-the-art spectroscopic approaches. <u>two primary approaches: spatial readout and temporal readout. Spatial readout maps spectral information to the spatial domain using spatial dispersive elements such as diffraction gratings [17], virtually imaged phased arrays (VIPAs) [18], and arrayed waveguide gratings [19], with parallel detection via cameras [20–22], but often faces a trade-off between speed and sensitivity. In contrast, temporal readout—often referred to as time-stretch [23–29]—maps spectral information into the time domain, enabling serial detection with a fast photodetector and supporting high-speed, sensitive measurements.</u>
2	Position: Page 3, Line 16 Change: we add this sentence and table 1. <u>86 femtometers (10 MHz) with a dispersion of -145.76 ns/nm. As summarized in Table 1, this represents more than an order-of-magnitude improvement over conventional single-shot spectroscopic methods. This breakthrough compensates for the</u>
3	Position: Page 3, Table 1 Change: We included a benchmarking table (Table 1) to highlight the relative performance and clarify the significance of the achieved 86 fm resolution.

Table 1 Comparison of high resolution single shot spectroscopic techniques					
Reference	Technique	Readout type	Spectral resolution	Year	Key limitation
[17]	Diffraction grating	Spatial	2.4 pm	2017	Optical path difference
[18]	VIPA	Spatial	4.5 pm	2024	Etalon's finesse
[19]	Array waveguided grating	Spatial	100 pm	2022	Optical path difference
[27]	Bidirectional time-stretch	Time	2.2 pm	2007	Time domain overlap
[28]	Resonator-based time-stretch	Time	24 pm	2017	Time domain overlap
[35]	Up conversion time-stretch	Time	1 pm	2023	Time domain overlap
This work	This work	Time	86 fm	2026	—

[1] Scheeline, A. How to design a spectrometer. Appl. Spectrosc. 71, 2237–2252 (2017).

[2] Zhou H, Zhao W, Cui W, et al. A simple spectrogram model for high-accuracy spectral calibration of VIPA spectrometers. Analyst, 149, 5455-5462, (2024).

[3] Zou, J., Sun, F., Wang, C. et al. Silicon-based arrayed waveguide gratings for WDM and spectroscopic analysis applications. Opt. Laser Technol. 147, 107656 (2022).

[4] Chou, J., Boyraz, O., Solli, D. & Jalali, B. Femtosecond real-time single-shot digitizer. Appl. Phys. Lett. 91, 161105 (2007).

[5] Weber S, Waller E H, Kaiser C, et al. Time-stretched real-time measurement technique for ultrafast absorption variations with TS/s sampling-rate. Optics Express, 25, 14125-14133, (2017).

[6] Hashimoto K, Nakamura T, Kageyama T, et al. Upconversion time-stretch infrared spectroscopy. Light Sci. Appl. 12, 48 (2023).

Response to Reviewer #2

General comment:

We thank the reviewer for the positive assessment of the experimental design and engineering innovation. We have carefully addressed the conceptual and contextual concerns

raised, as detailed below.

1. The authors mainly compare their system with Fourier-transform infrared (FTIR) spectrometers; however, FTIR does not fully represent the current state of the art in single-shot or ultrafast spectroscopy. The statement “No other technique achieves this level of single-shot resolution” also appears overstated. How does the system compare with recent dual-comb or electro-optic comb spectroscopy methods, and does its resolution differ by orders of magnitude from other time-stretch-based spectroscopic approaches?

Response: We thank you for this important and insightful comment. We agree that a broader comparison beyond FTIR is necessary to properly position the present work with respect to the state of the art. In addition to FTIR, advanced spectroscopic techniques such as dual-comb spectroscopy and electro-optic comb spectroscopy have demonstrated exceptionally high spectral resolution, reaching the kHz–MHz regime.

However, these comb-based approaches are subject to intrinsic trade-offs between spectral resolution, bandwidth, and acquisition rate. In dual-comb spectroscopy [1], under a fixed repetition rate difference (equal to acquisition rate), achieving very high spectral resolution requires a small comb spacing, which consequently limits the accessible spectral bandwidth. Similarly, in electro-optic comb spectroscopy [2], the achievable bandwidth is constrained by the finite number of comb lines, such that small comb spacing (high resolution) typically results in a bandwidth limited to the GHz range. More importantly, both approaches rely on heterodyne detection, where the optical spectrum is mapped to the radio frequency (RF) domain and reconstructed through electrical signal analysis. In practice, achieving high resolution typically requires temporal averaging or sequential acquisition to ensure sufficient signal-to-noise ratio and frequency stability. Therefore, they do not constitute single-shot operation.

In contrast, the present work focuses on single-shot spectroscopy, where the full spectrum is acquired from a single optical pulse without averaging or reconstruction. As discussed in the revised manuscript, we have added a quantitative comparison with representative time-stretch spectrometers in Table 1, which are directly comparable within the single-shot framework. Existing time-stretch systems typically achieve spectral resolution on the order of several picometers due to the intrinsic trade-off among dispersion, bandwidth, and acquisition rate. By introducing reconfigurable time-stretch architecture with programmable control of dispersion and acquisition parameters, our system enables operation near the extreme limit of this trade-off space while maintaining true single-shot capability. As a result, we achieve a spectral resolution of 86 femtometers in a single-shot measurement, representing more than one order of magnitude improvement over previously reported time-stretch spectrometers. We have reorganized the introduction and revised the manuscript accordingly to clarify these distinctions and to provide a more consistent comparison framework in Table 1.

We have added discussion on resolution of different approaches, as well as table 1 in the revised manuscript.

No.	Modification
1	Position: Page 2, Line 2 Change: We modified the introduction by adding a broader and more quantitative comparison with state-of-the-art techniques, including dual-comb and electro-optic comb spectroscopy. ² Beyond traditional Michelson-based Fourier transform spectroscopy (MFTS), sub- ³ stantial efforts have been devoted to the development of advanced spectroscopic ⁴ approaches, including dual-comb frequency comb spectroscopy (DFCS) [1], electro- ⁵ optic comb spectroscopy [2], tunable optical filter spectroscopy [3] microresonator- ⁶ based comb spectroscopy [4], and integrated reconstructive spectroscopy based on ⁷ Mach-Zehnder interferometer chips [5]. The latter two approaches provide compact ⁸ and integrated solutions, and filter-based spectroscopies are relatively easy to imple- ⁹ ment, whereas the former comb-based spectroscopies offer superior performance, ¹⁰ achieving spectral resolutions down to the kilohertz-megahertz regime. However, these ¹¹ approaches are fundamentally constrained by intrinsic trade-offs among spectral res- ¹² olution, bandwidth, and acquisition rate [6], where achieving ultrahigh resolution ¹³ typically comes at the expense of limited spectral bandwidth. More importantly, all ¹⁴ these approaches rely on heterodyne detection, in which optical spectra are mapped ¹⁵ to the radio frequency (RF) domain and reconstructed through electrical signal pro- ¹⁶ cessing. In practice, they require temporal averaging or scanning in RF domain to ¹⁷ ensure sufficient signal to noise ratio. These characteristics prevent them from consti- ¹⁸ tuting single-shot spectroscopy, where a complete spectrum is acquired within a single ¹⁹ measurement event.
2	Position: Page 3, Line 16 Change: we add this sentence and table 1. ¹⁶ 86 femtometers (10 MHz) with a dispersion of -145.76 ns/nm. As summarized in ¹⁷ Table 1, this represents more than an order-of-magnitude improvement over con- ¹⁸ ventional single-shot spectroscopic methods. This breakthrough compensates for the
3	Position: Page 3, Table 1 Change: We included a benchmarking table (Table 1) to highlight the relative performance and clarify the significance of the achieved 86 fm resolution.

 Table 1 Comparison of high resolution single shot spectroscopic techniques					
Reference	Technique	Readout type	Spectral resolution	Year	Key limitation
[17]	Diffraction grating	Spatial	2.4 pm	2017	Optical path difference
[18]	VIPA	Spatial	4.5 pm	2024	Etalon's finesse
[19]	Array waveguided grating	Spatial	100 pm	2022	Optical path difference
[27]	Bidirectional time-stretch	Time	2.2 pm	2007	Time domain overlap
[28]	Resonator-based time-stretch	Time	24 pm	2017	Time domain overlap
[35]	Up conversion time-stretch	Time	1 pm	2023	Time domain overlap
This work	This work	Time	86 fm	2026	—

[1] Coddington, I., Newbury, N. & Swann, W. Dual-comb spectroscopy. *Optica* 3, 414–426 (2016).

[2] Parriaux, A., Hammani, K. & Millot, G. Electro-optic frequency combs. *Adv. Opt. Photon.* 12, 223–287 (2020).

2. The manuscript claims to “overcome” the trade-off between bandwidth, resolution, and acquisition speed, yet the results indicate resolution is improved by sacrificing speed. Does the system truly resolve this limitation, or merely allow switching between different trade-off regimes?

Response: We thank you for this insightful comment. You are correct that no spectrometer can completely eliminate the trade-off between spectral resolution, bandwidth, and acquisition speed, as this constraint arises from fundamental physical limitations and is inherent to essentially all spectrometer architectures.

Our approach does not eliminate this trade-off but instead provides a programmable framework to navigate it. Specifically, the reconfigurable time-stretch architecture enables flexible control of dispersion and acquisition parameters, allowing the system to operate at different points within the trade-off space depending on the measurement objective. This capability allows selective optimization of performance metrics, such as achieving ultrahigh spectral resolution or high acquisition speed, under different configurations.

Importantly, this reconfigurability enables rapid switching between parameter configurations on a millisecond timescale, allowing the same system to probe a dynamic process under multiple measurement conditions. This is particularly advantageous for capturing complex spectral dynamics, where different temporal and spectral resolutions may be required to fully resolve the underlying physical processes. We agree that the term “overcome” was not sufficiently precise and have revised the manuscript to replace it with “enable programmable navigation of the trade-off between spectral resolution, bandwidth, and acquisition speed” or “enabling operation across different regions of the trade-off space”.

No.	Modification
1	Position: Page 1, Line 21 Change: We revised the manuscript to replace the term "overcome" with more precise phrasing, clarifying that the system enables programmable navigation of the trade-off space rather than eliminating the fundamental constraint. 19 ing their versatility and broader adoption. Here, we introduce a reconfigurable 20 single-shot spectroscopy method that offers full programmability over spectral 21 bandwidth, resolution, and acquisition speed, <u>enabling programmable navigation</u> 22 <u>of the trade-off</u>. By selecting optimal configurations, our approach compensates
2	Position: Page 3, Line 8 Change: We revised the manuscript to replace the term "overcome" with more precise phrasing, clarifying that the system enables programmable navigation of the trade-off space rather than eliminating the fundamental constraint. 4 In this work, we present a solution to the challenge of balancing spectral 5 bandwidth, resolution, and acquisition speed in single-shot spectroscopy. Our recon- 6 figurability architecture integrates a tunable optical filter, a dispersion-programmable 7 loop with amplification, and a pulse picker, enabling coordinated and programmable 8 control of key system parameters. <u>The proposed system enables single-shot spec-</u> 9 <u>tral acquisition with programmable control of spectral resolution, bandwidth, and</u> 10 <u>acquisition rate. The reconfigurability is implemented between successive single-shot</u> 11 <u>measurements, allowing each pulse to be measured under a distinct, user-defined sys-</u> 12 <u>tem configuration. This approach facilitates a significant enhancement in spectral</u> 13 <u>resolution by increasing dispersion at the cost of bandwidth or acquisition speed.</u>
3	Position: Page 11, Line 32 Change: We modified this sentence rather than use “overcome”. 32 ing of system parameters. <u>This method enables flexible operation beyond the fixed</u> 33 <u>figures of merit inherent in traditional spectroscopic techniques, providing the ability</u> 34 <u>to adapt system performance to specific application requirements.</u> We present proof-

3. Since the current PS-FBG/PZT test remains a static or quasi-periodic case. Could the authors demonstrate or discuss whether the system can perform transient absorption spectroscopy or equivalent single-shot transient measurements, which would better substantiate its claimed advantage for ultrafast dynamics?

Response: We thank you for this insightful comment. We agree that the term “ultrafast dynamics” in the original manuscript may be misleading, as it is typically associated with femtosecond–picosecond pump–probe spectroscopy rather than real-time single-shot measurements. To avoid confusion, we have revised the manuscript to replace “ultrafast processes” with “rapid and non-repetitive processes,” which more accurately reflects the temporal regime addressed in this work. We would also like to clarify that our work does not aim to claim an advantage in ultrafast (femtosecond–picosecond) dynamics, but instead focuses on real-time, single-shot spectroscopy of rapidly evolving spectral processes.

The manuscript includes static, quasi-periodic, and transient spectral measurements, each serving a distinct purpose. Specifically, the results in, Fig. 3 and, Fig. 4 correspond to static absorption measurements, while the sinusoidal excitation in, Fig. 5(c,d,f,g) is intentionally introduced to provide controlled and repeatable quasi-periodic spectral modulation, which is widely used to quantitatively validate spectral resolution, temporal response, and measurement accuracy. Importantly, transient spectral measurements are demonstrated using abrupt pulsed excitation, as shown in, Fig. 5(b,e,h), where the stimulus duration is shorter than 100 μ s. These represent genuine transient events rather than periodic modulation. We acknowledge that this aspect was not sufficiently emphasized in the original manuscript and have clarified it in the revised version. Such microsecond-scale dynamics fall within the characteristic timescales of many fast physical and chemical processes, including combustion, plasma evolution, and shockwave-induced spectral changes, consistent with prior reports [1,2].

In response to the reviewer’s question regarding transient absorption spectroscopy, we emphasize that the key strength of the proposed system lies in its ability to perform real-time, single-shot measurements without temporal averaging or scanning. Since each optical pulse encodes a complete spectrum, the system enables direct capture of transient spectral evolution in rapidly evolving and non-repetitive scenarios. The transient experiments presented in, Fig. 5(b,e,h) therefore substantiate this capability within the relevant temporal regime for practical applications. To further clarify this distinction, we have revised the manuscript to better differentiate between ultrafast spectroscopy and real-time single-shot spectroscopy, and added corresponding discussion and references.

No.	Modification
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1	Position: Page 1, Line 13 Change: We modified the manuscript , replacing “ultrafast processes” with “rapid and non-repetitive processes”. 12 Single-shot spectroscopy enables the capture of an entire transient event within 13 a single measurement, <u>providing critical insights into rapid and non-repetitive</u> 14 <u>processes</u> across diverse fields such as biomedical diagnostics, environmental mon- 15 itoring, material stress analysis, advanced manufacturing, and telecommunication 16 network fluctuation detection. Despite its promise, current single-shot spectro-
2	Position: Page 9, Line 10 Change: we replace “ultrafast” to real time. 10 To demonstrate the real-time capabilities of the proposed spectroscopy system, we 11 employed it to capture the rapid dynamics of a PS-FBG. Given the minimal wave- 12 length drift induced by strain, there is a critical need for both high resolution and
3	Position: Page 12, Line 8 Change: we replace “ultrafast” to real time. 5 method to mid-infrared spectroscopy. In terms of acquisition speed, the use of a high 6 repetition rate MLL [39], combined with the replacement of the AOM in the pulse 7 picker with a high-speed, high-extinction-ratio electro-optic modulator [40], could 8 enable sampling rates in the tens of gigahertz range to capture real time dynamics, 9 enabling the exploration of phenomena at even shorter timescales. In conclusion, the
4	Position: Page 11, Line 3 Change: We expanded the discussion of transient measurements (Fig. 5) to demonstrate the system's capability for real-time single-shot capture of microsecond-scale spectral dynamics. 1 PS-FBG. As shown in Fig. 5(c), a wavelength shift as small as 238.8 fm is observed. To 2 simulate a more rapid vibrational response, the frequency of the sinewave is increased 3 to 9 kHz. <u>Fig. 5(d) and (g) display the measured results over a 333 μs observation</u> 4 <u>window, capturing three excitation cycles. While the abrupt excitation (Fig. 5 e,h)</u> 5 <u>demonstrates the capability for transient spectral measurements. The abrupt excita-</u> 6 <u>tion (<100 μs) represents a transient spectral event within the characteristic timescale</u> 7 <u>of combustion and shockwave induced spectral dynamics, demonstrating the capabil-</u> 8 <u>ity of the system to capture rapid transient spectral responses. Fig. 5(e) shows an</u>

References

- [1] Kubota, S., Shinohara, S., Kurokawa, T. & Azaña, J. Ultrafast transient absorption spectroscopy using dispersive Fourier transform. *Optica* **4**, 110–115 (2017).
- [2] Hanson, R. K. Applications of quantitative laser sensors to kinetics, propulsion and practical energy systems. *Proceedings of the Combustion Institute* **33**, 1–40 (2011).

[3] Goda, K. & Jalali, B. Dispersive Fourier transformation for fast continuous single-shot measurements. *Nature Photonics* **7**, 102–112 (2013).

[4] Ling, H. Y., Lau, K. T. & Zhou, L. Fiber Bragg grating sensing of shock waves. *Optics Letters* **30**, 2975–2977 (2005).

4. The setup includes multiple AOMs, MEMS switches, EDFAs, and long DCF fibers, making it complex and environmentally sensitive. How might these challenges be addressed for integration or real-world use?

Response: We thank you for this important comment. We agree that the current laboratory implementation involves multiple components, including AOMs, MEMS switches, EDFAs, and dispersion fibers. However, all these components are mature telecom-grade fiber-optic devices that have been extensively developed and deployed in optical communication systems operating in the 1550 nm band. For example, EDFAs and dispersion-compensating fibers are standard components in long-haul transmission systems, while high-speed optical modulation and switching technologies are widely used in modern optical networks. These systems have been successfully productized and deployed at large scale, demonstrating excellent stability, reliability, and environmental robustness.

In addition, the entire system is implemented in a fiber-integrated configuration without free-space optical alignment, which significantly improves mechanical stability and reduces environmental sensitivity compared to free-space systems. This architecture inherently enhances robustness against vibration, misalignment, and thermal fluctuations, making it well suited for practical deployment.

Looking forward, further integration and miniaturization can be achieved using existing photonic integration technologies. For example, dispersion elements can be implemented using chirped fiber Bragg gratings (CFBGs) [1] to provide large dispersion with less loss, while fast optical switching and modulation functions can be realized using Thin-film lithium niobate [2]. In addition, system-level engineering approaches, including optimized packaging, thermal management, and vibration isolation, can be applied to further improve stability and compactness. These approaches are well established in telecom and photonic instrumentation, supporting the feasibility of translating the current system into a compact and robust instrument. We have added corresponding discussion and references in the revised manuscript.

Modification
Position: Page 12, Line 15 Change: We modified the manuscript by adding discussion on system integration and practical implementation, including the use of mature fiber-optic components, fully

fiber-integrated architecture, and potential photonic integration solutions, to address concerns on complexity and environmental robustness.

research. Although the current implementation involves multiple discrete components, all elements are based on mature telecom-grade fiber-optic technologies operating in the 1550 nm band, which ensures high stability, reliability, and environmental robustness. Fully fiber-integrated architecture eliminates free-space optical alignment, significantly reducing sensitivity to vibration, misalignment, and thermal fluctuations. Further integration and miniaturization can be achieved using established photonic technologies. For example, dispersive elements can be implemented using chirped fiber Bragg gratings while switching and modulation functions can be realized using thin-film lithium niobate technique. Together with standard system-level engineering approaches, such as optimized packaging, thermal management, and vibration isolation, these advances support the feasibility of translating the current system into a compact and robust instrument for real-world applications.

References

[1] Gharat, A., Nawale, P., Waje, P. et al. Performance analysis of CFBG and DCF based on dispersion compensation. In 2020 IEEE Int. Students' Conf. Electrical, Electronics and Computer Science (SCEECS), 1–5 (IEEE, 2020).

[2] Zhu, D., Shao, L., Yu, M. et al. Integrated photonics on thin-film lithium niobate. *Adv. Opt. Photon.* 13, 242–352 (2021).

5. The “fully programmable” claim remains qualitative. Could the authors provide a quantitative model or numerical analysis that more clearly demonstrates how programmability enables simultaneous adjustment of bandwidth, resolution, and acquisition rate?

Response: We thank you for this important comment. We agree that the programmability of the system should be described in a more quantitative and structured manner. In this work, programmability refers to the ability to dynamically control key system parameters that determine the trade-off among spectral resolution, bandwidth, and acquisition rate, as described by Eqs. (5) and (6), thereby enabling operation at different points within this trade-off space.

Specifically, this programmability is realized through coordinated control of four temporal gating operations. AOM1 performs pulse picking to determine the acquisition rate. AOM2 defines the effective loop gating time, which is governed by the number of loop circulations and the per-loop delay, thereby controlling the total dispersion and spectral resolution.

AOM3 defines the temporal window of the stretched pulse, which sets the minimum duration required for spectral filtering and is therefore directly related to the achievable spectral bandwidth. To clarify this mechanism, we have added a programmable control diagram (Fig. 3), including timing diagrams of representative configurations.

Furthermore, to provide a quantitative description, we define three representative operating modes—broadband high-resolution, high-speed broadband, and high-speed high-resolution—consistent with the configurations used in, Fig. 3(a). These modes correspond to distinct operating points within the resolution–bandwidth–acquisition-rate trade-off space. The associated control parameters and resulting performance metrics are summarized in, Fig. 3(d), establishing a direct mapping between programmable system parameters and achievable spectrometer performance. For clarity, this programmable control diagram is presented in the revised manuscript, so that the experimental results can be directly interpreted as specific realizations of these operating modes.

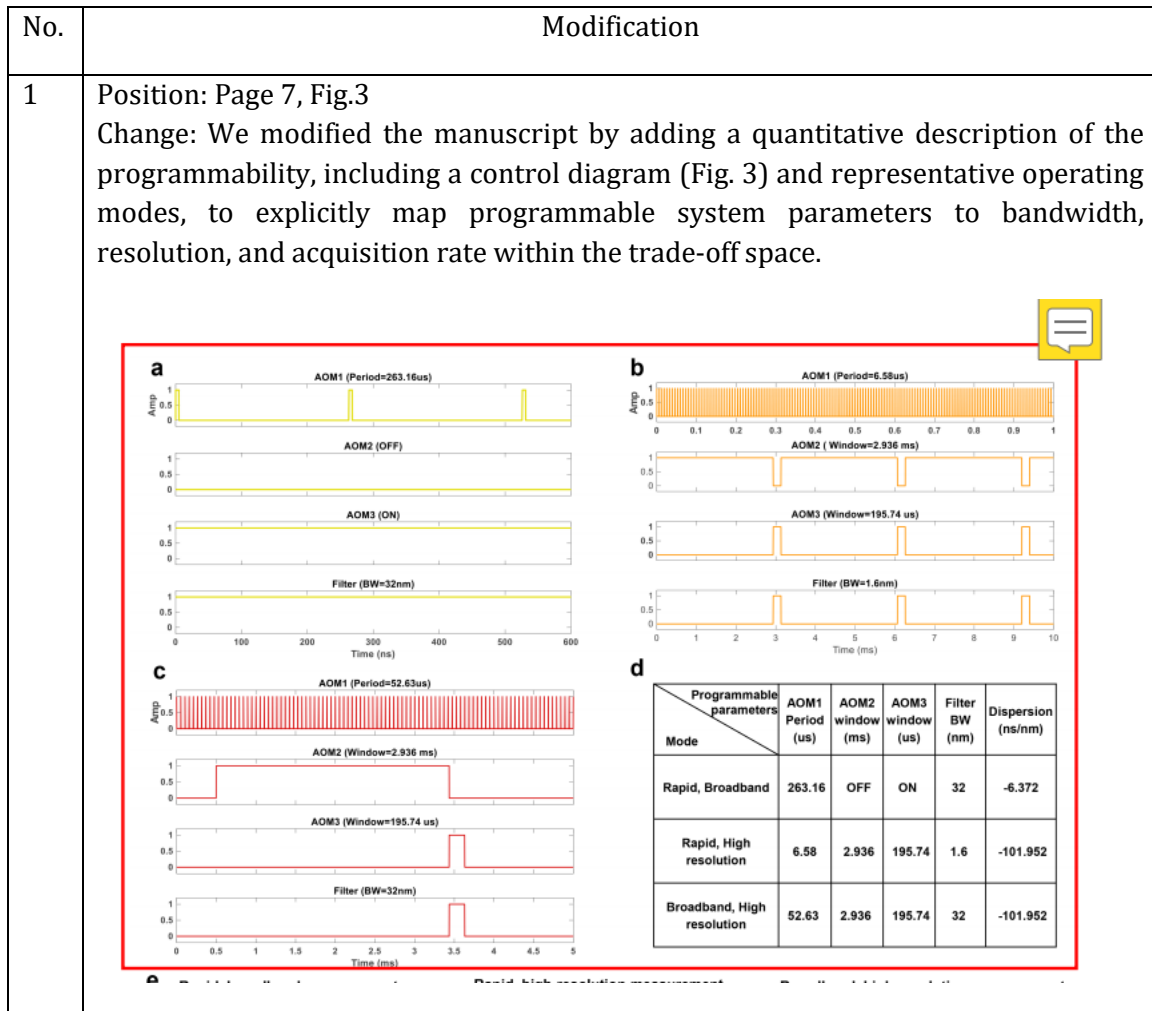


	Fig. 3 Programmable operation of the system. (a–c) Timing diagrams illustrating three representative operating modes: broadband high resolution, rapid broadband, and rapid high resolution. The coordinated control of AOM1 (pulse picking), AOM2 (loop gating), and AOM3 (temporal window) enables dynamic adjustment of acquisition rate, total dispersion, and temporal stretching, which determines spectral resolution, bandwidth, and acquisition speed. (d) Summary of the programmable control parameters and corresponding performance metrics for the three modes. Each mode represents a distinct operating point within the resolution–bandwidth–acquisition-rate trade-off space. (e)
2	Position: Page 7, Line 1 Change: We modified the manuscript by adding a quantitative description of the programmability, including a control diagram (Fig. 3) and representative operating modes, to explicitly map programmable system parameters to bandwidth, resolution, and acquisition rate within the trade-off space. 1 Considering the constraint relationship described, only two of the figures of merit 2 (FOMs) can be optimized in a single setup, necessitating the sacrifice of the third. To 3 quantitatively illustrate the programmability of the proposed spectroscopy, we define 4 a set of representative operating modes based on coordinated control of system param- 5 eters. As shown in Fig. 3, programmability is realized through synchronized temporal 6 gating operations that jointly determine the acquisition rate, total dispersion, and
3	Position: Page 8, Line 1 Change: We modified the manuscript by adding a quantitative description of the programmability, including a control diagram (Fig. 3) and representative operating modes, to explicitly map programmable system parameters to bandwidth, resolution, and acquisition rate within the trade-off space. 1 effective temporal window of the optical filter, which in turn define the measurement 2 speed, spectral resolution, and bandwidth within the trade-off space described by 3 Eq.(5) and Eq.(6). Specifically, this control is implemented through pulse picking to 4 set the acquisition rate, loop gating to control the effective dispersion via the number 5 of circulations and round-trip delay, and temporal windowing to match the stretched 6 pulse duration and filtering process, as illustrated by the representative timing con- 7 figurations in Fig. 3(a–c). Based on this framework, three representative operating 8 modes, broadband high resolution, rapid broadband, and rapid high resolution are 9 defined, each corresponding to a distinct operating point implemented through a 10 specific combination of programmable control parameters, as summarized in Fig. 3(d).

We sincerely thank the Reviewers again for their valuable feedback. We believe that the revisions have substantially strengthened the manuscript and hope that it is now suitable for publication in Nature Communications.

Sincerely,
Tianwei Jiang
on behalf of all authors