Rapid and high signal to noise ratio dual frequency comb spectroscopy

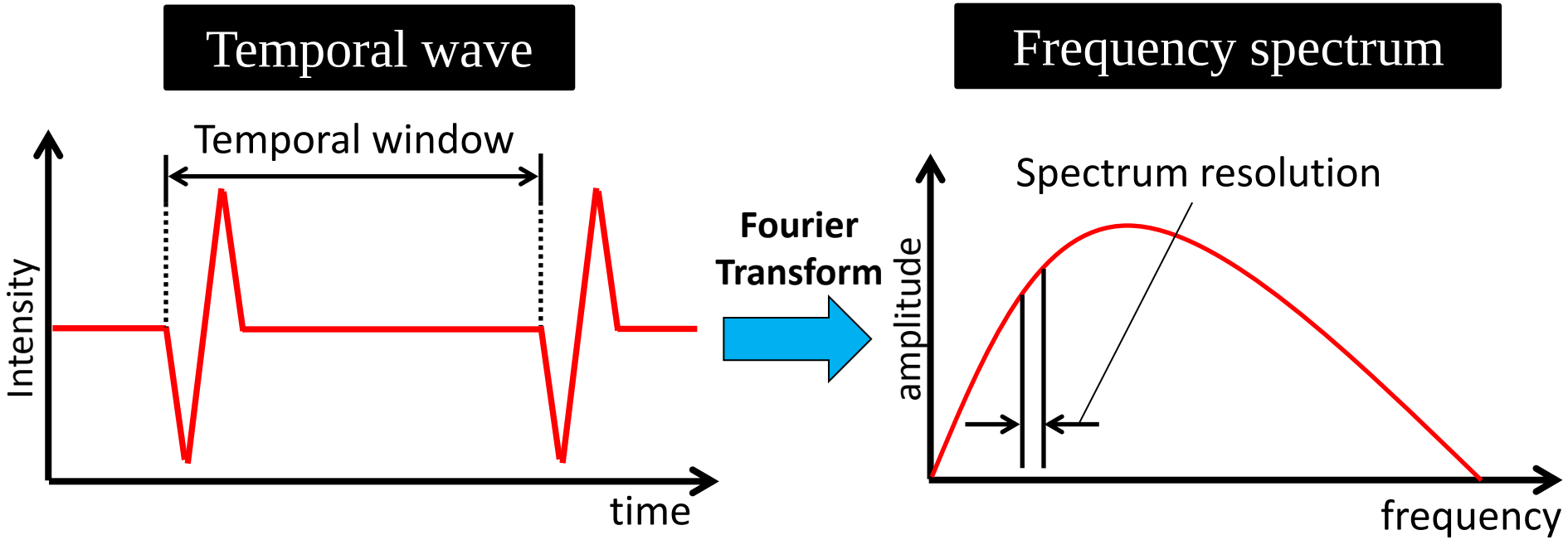
2014 / 5 / 21　M2　Ichikawa

- A. Schliesser, M. Brehm, and F. Keilmann, “Frequency-comb infrared spectrometer for rapid, remote chemical sensing”, Opt. Express **13**, 9029 (2005).

- F. Zhu, T. Mohamed, J. Strohaber, A. A. Kolomenskii, Th. Udem, and H. A. Schuessler, “Real-time dual frequency comb spectroscopy in the near infrared”, Appl. Phys. Lett., **102**, 121116 (2013).

- A. M. Zolot, F. R. Giorgetta, E. Baumann, J. W. Nicholson, I. Coddington, and N. R. Newbury, “Direct-comb molecular spectroscopy with accurate,resolved comb teeth over 43 THz”, OPTICS LETTER, **37**, 638(2012).

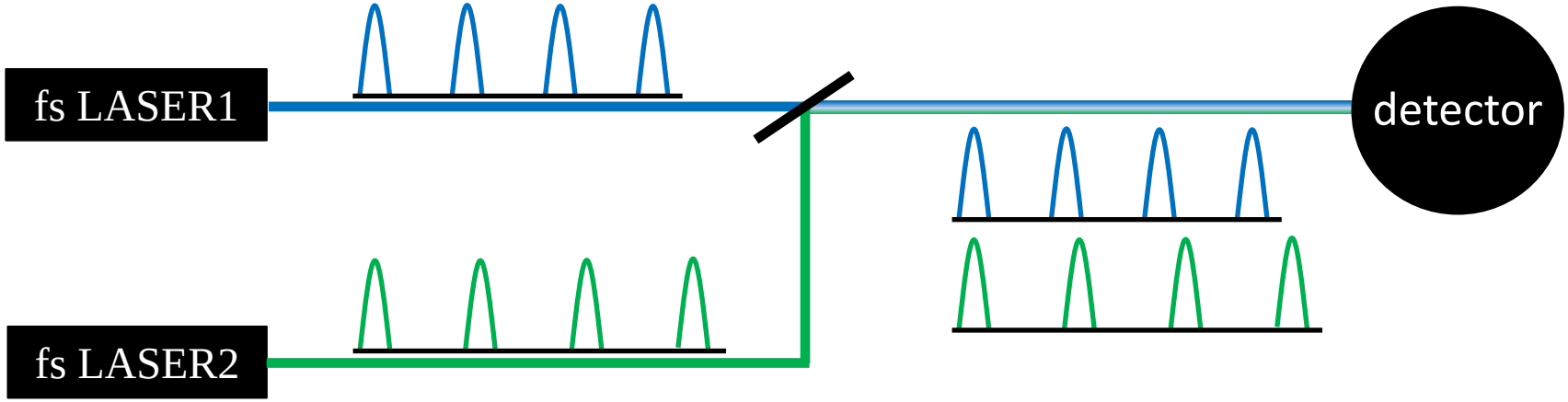
Fourier transform spectroscopy



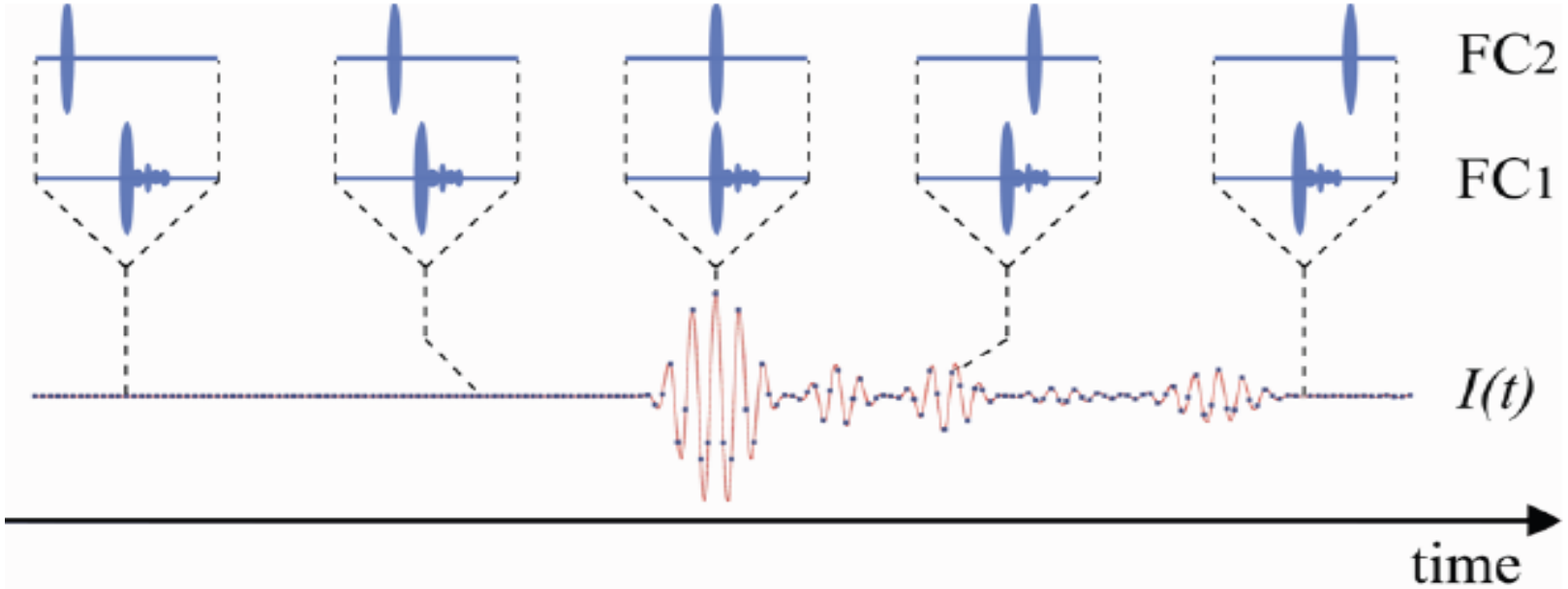
spectrum resolution＝
1 / temporal window

Accuracy ＝
Precision of time delay

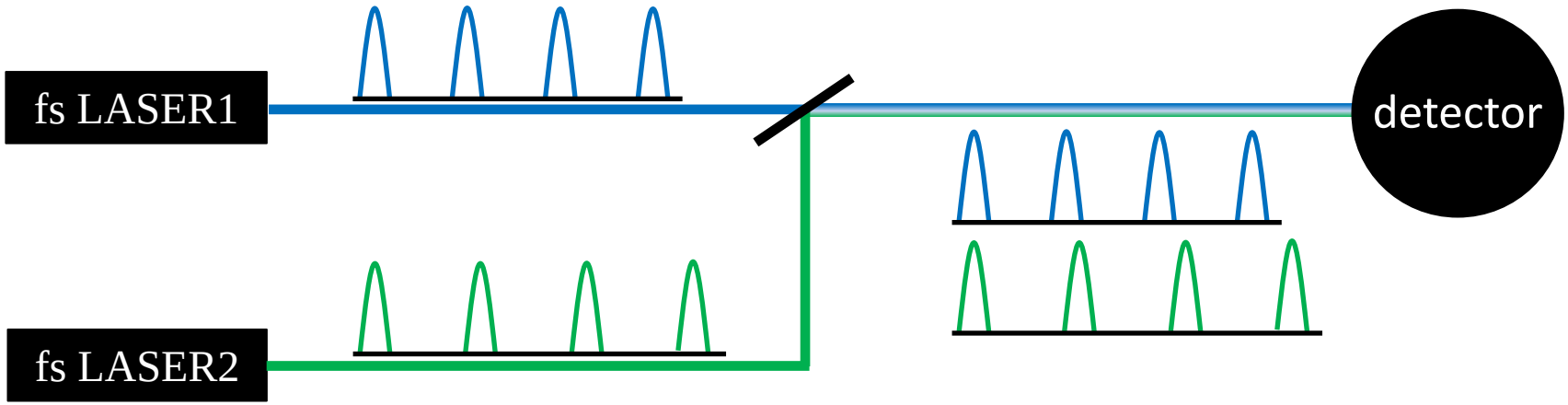
Dual frequency comb spectroscopy



Time domain

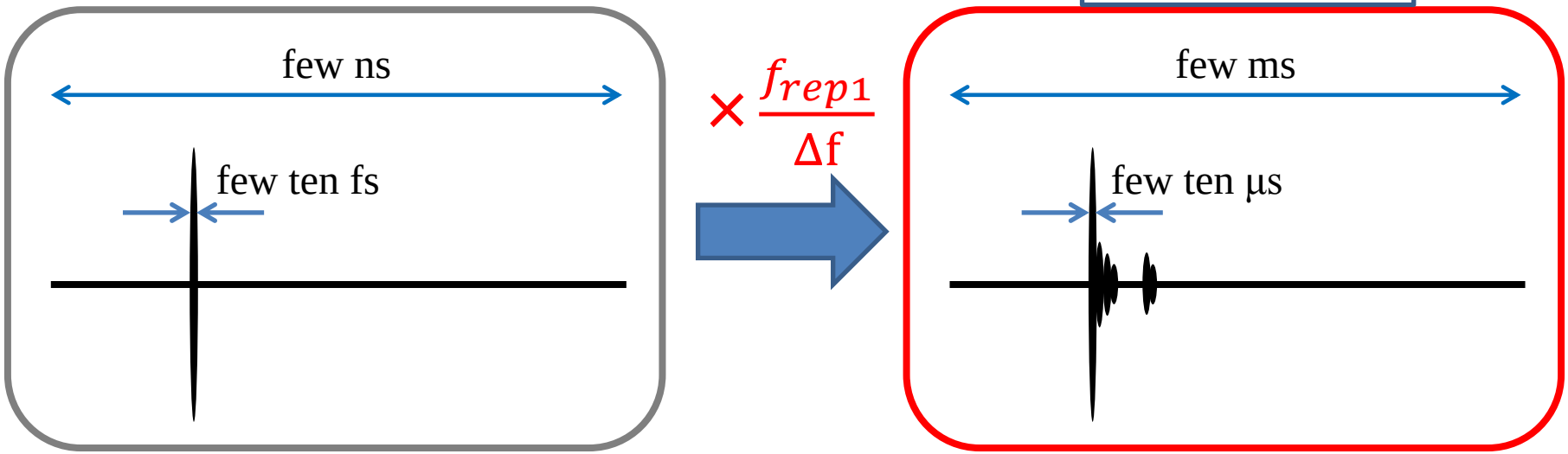


Dual frequency comb spectroscopy

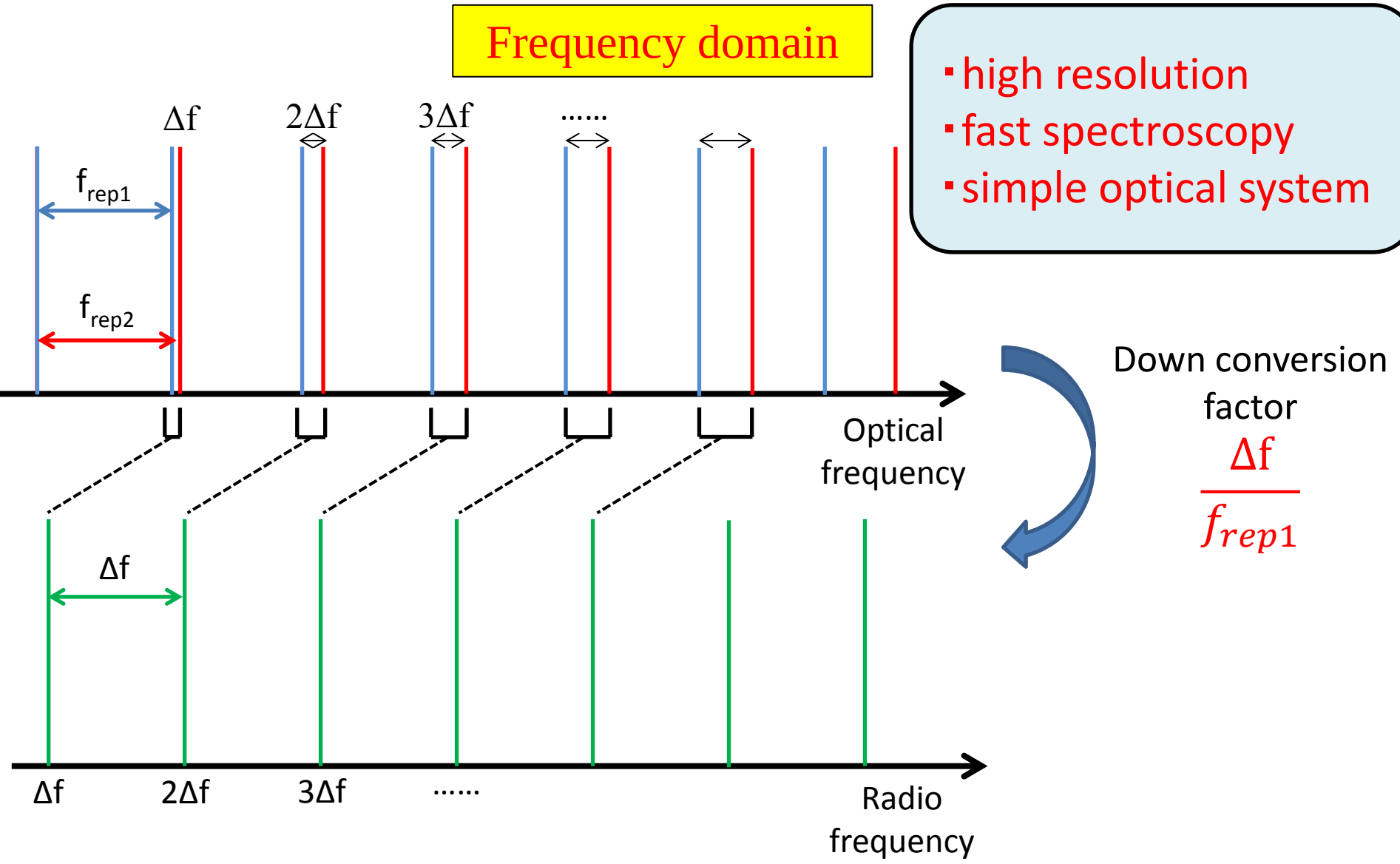


Time domain

Interferogram



Dual frequency comb spectroscopy

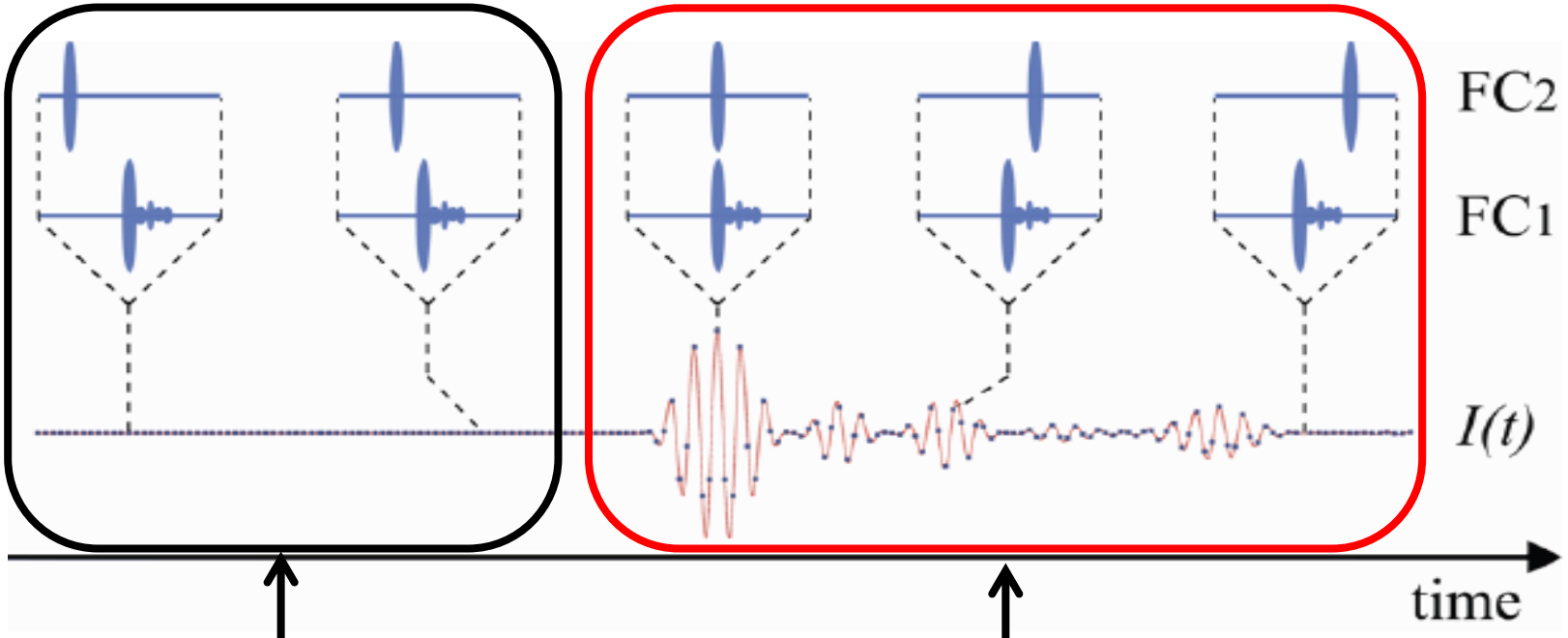


- high resolution
- fast spectroscopy
- simple optical system

Down conversion factor

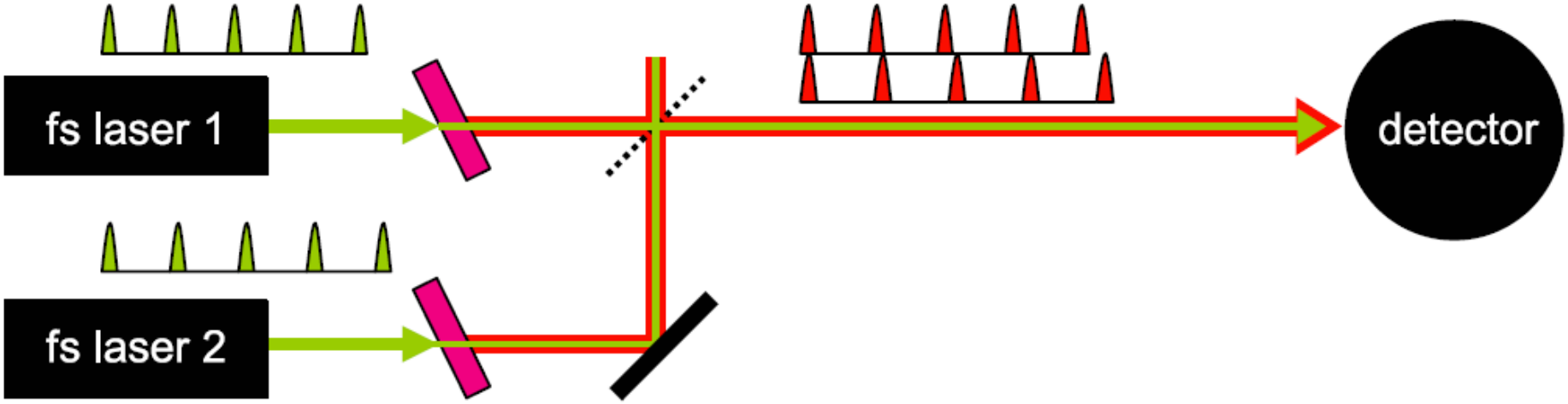
$$\frac{\Delta f}{f_{rep1}}$$

“Frequency-comb infrared spectrometer for rapid, remote chemical sensing”



In this letter, they changed repetition frequency to accelerate spectrum repetition.

Setup

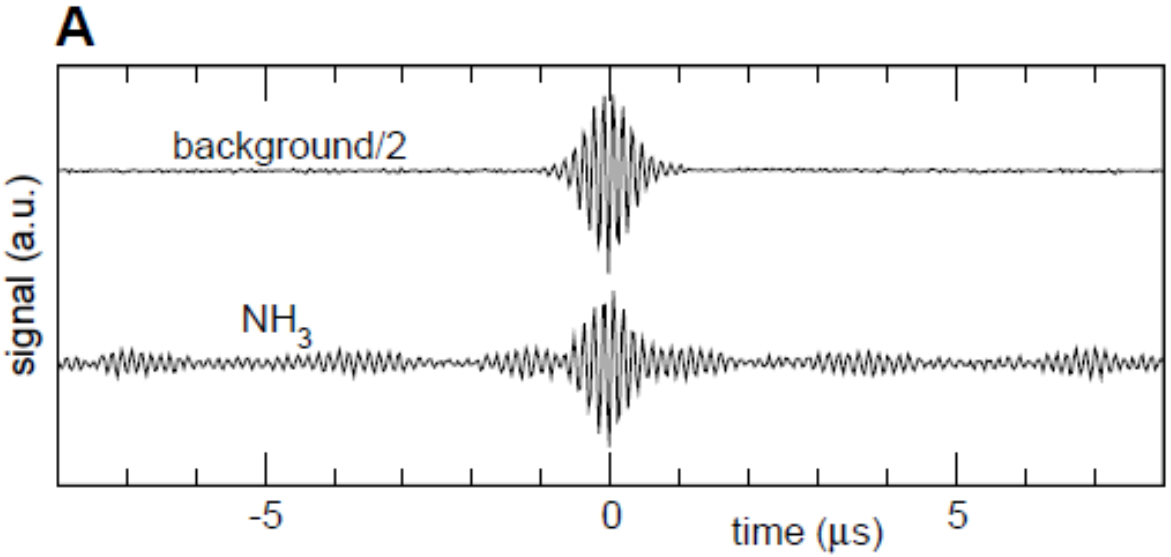


Ti : S Laser

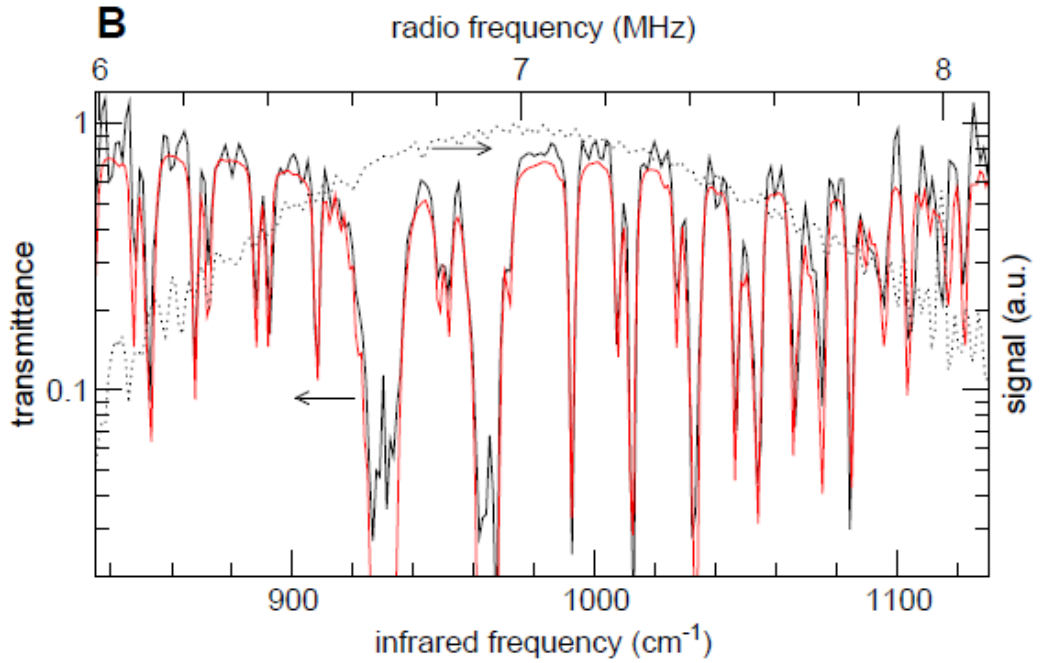
- Center wavelength : 800nm
- Pulse width : 10fs
- Average power : 500mW
- Repetition rate : 125.130MHz

Detector : HgCdTe detector
Emitter : GaSe crystals

Interferogram and spectrum



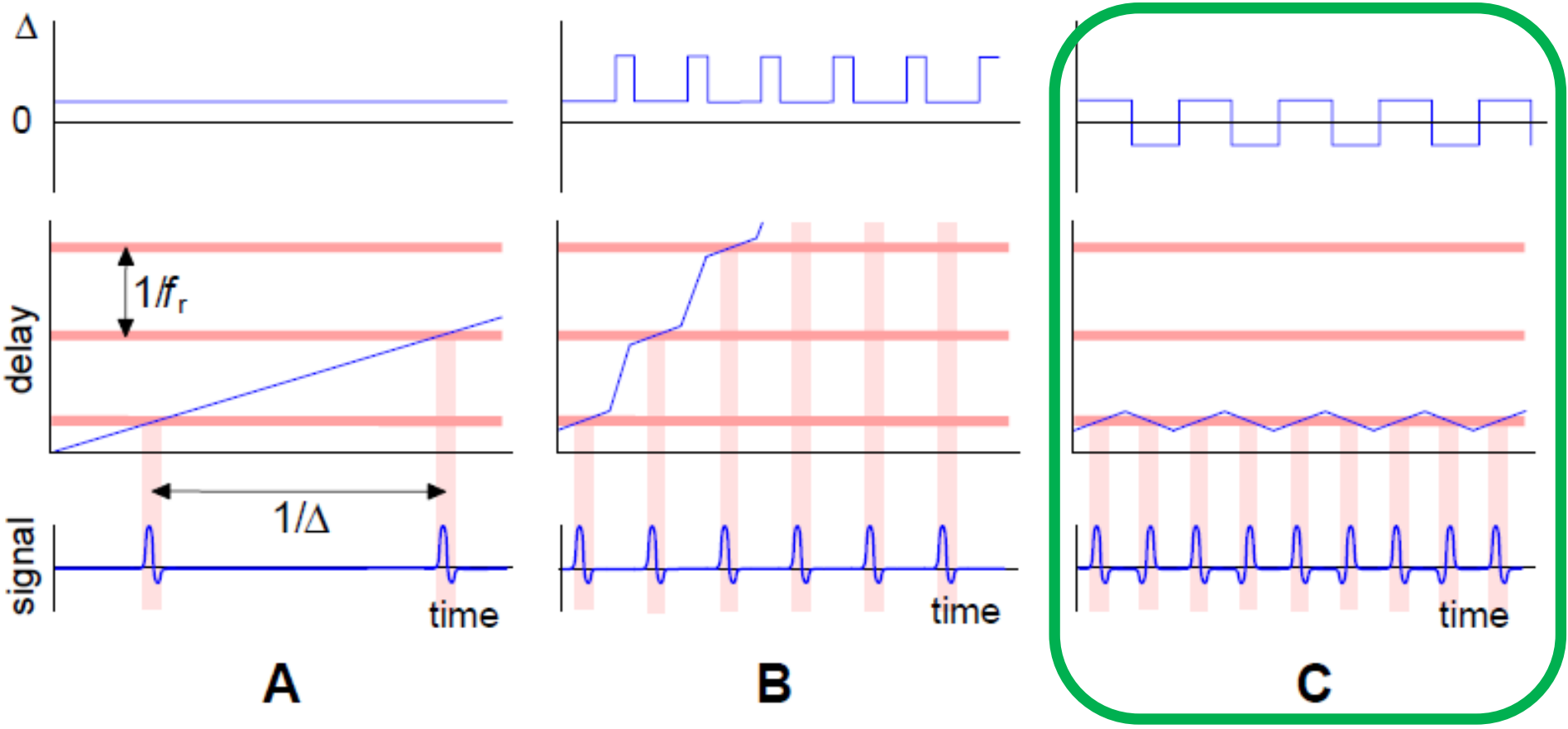
temporal window is 70µs (16µs displayed).
Δ = 29.93Hz.



Dotted : background.
Black : transmittance.
Red : conventional FTIR (60s acquisition time and 32spectra averaged).

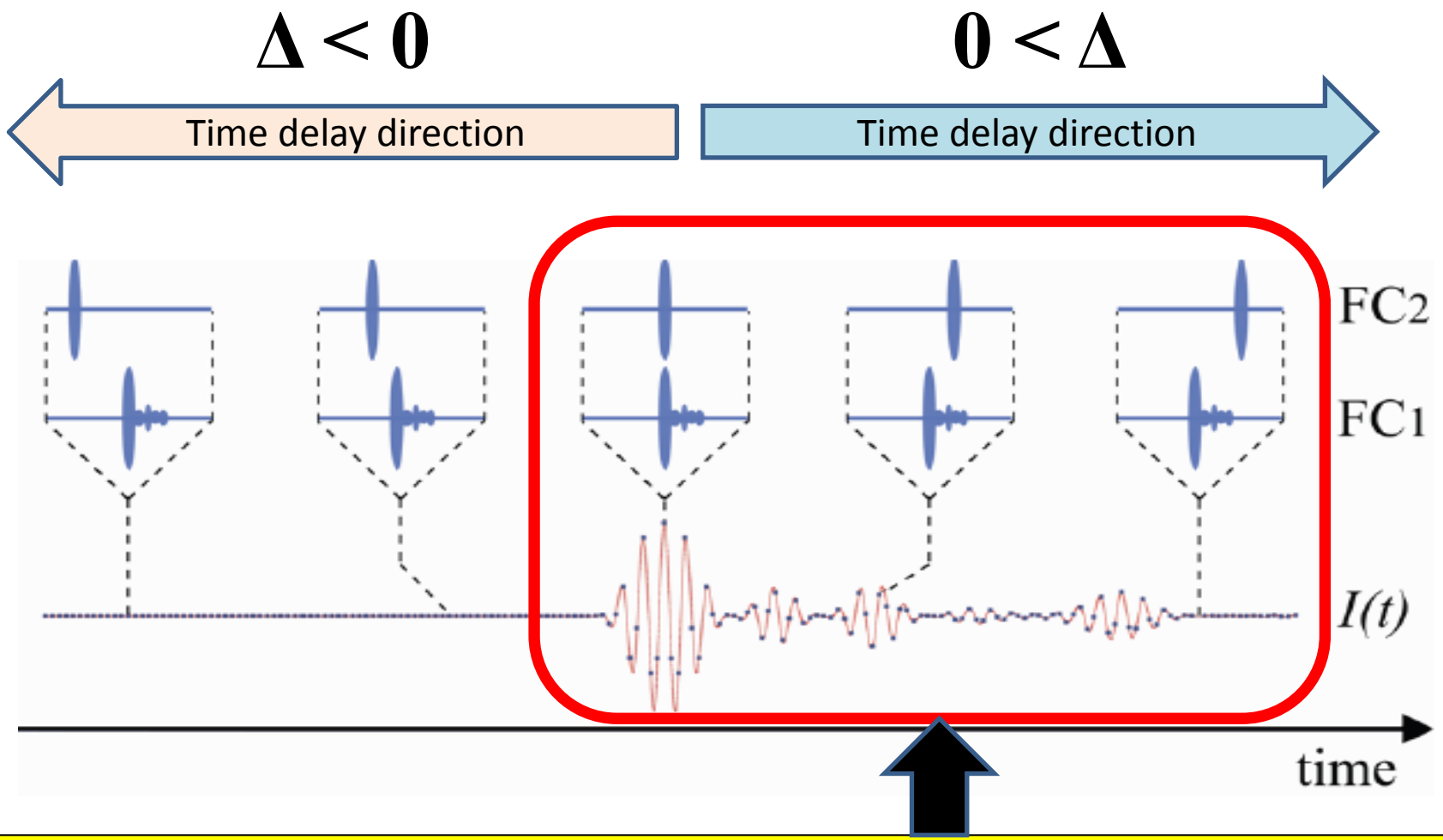
Resolusion : $2cm^{-1}$.

Accelerate spectrum repetition



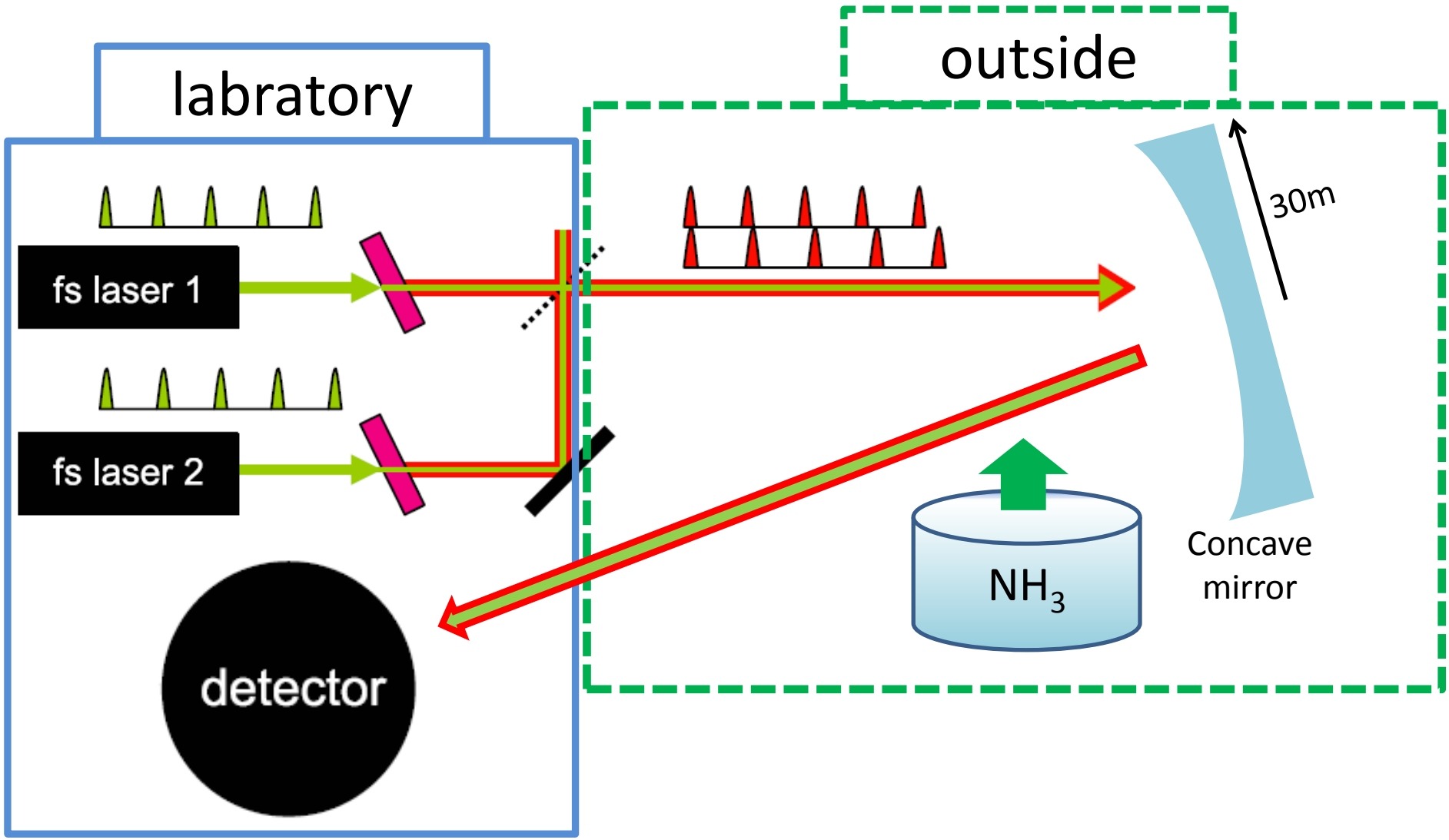
Method C is changing the value of $\Delta(=f_{rep1} - f_{rep2})$ after an interferogram recording, by manipulation of one of the laser's repetition frequency. = **no waiting time**

Accelerate spectrum repetition

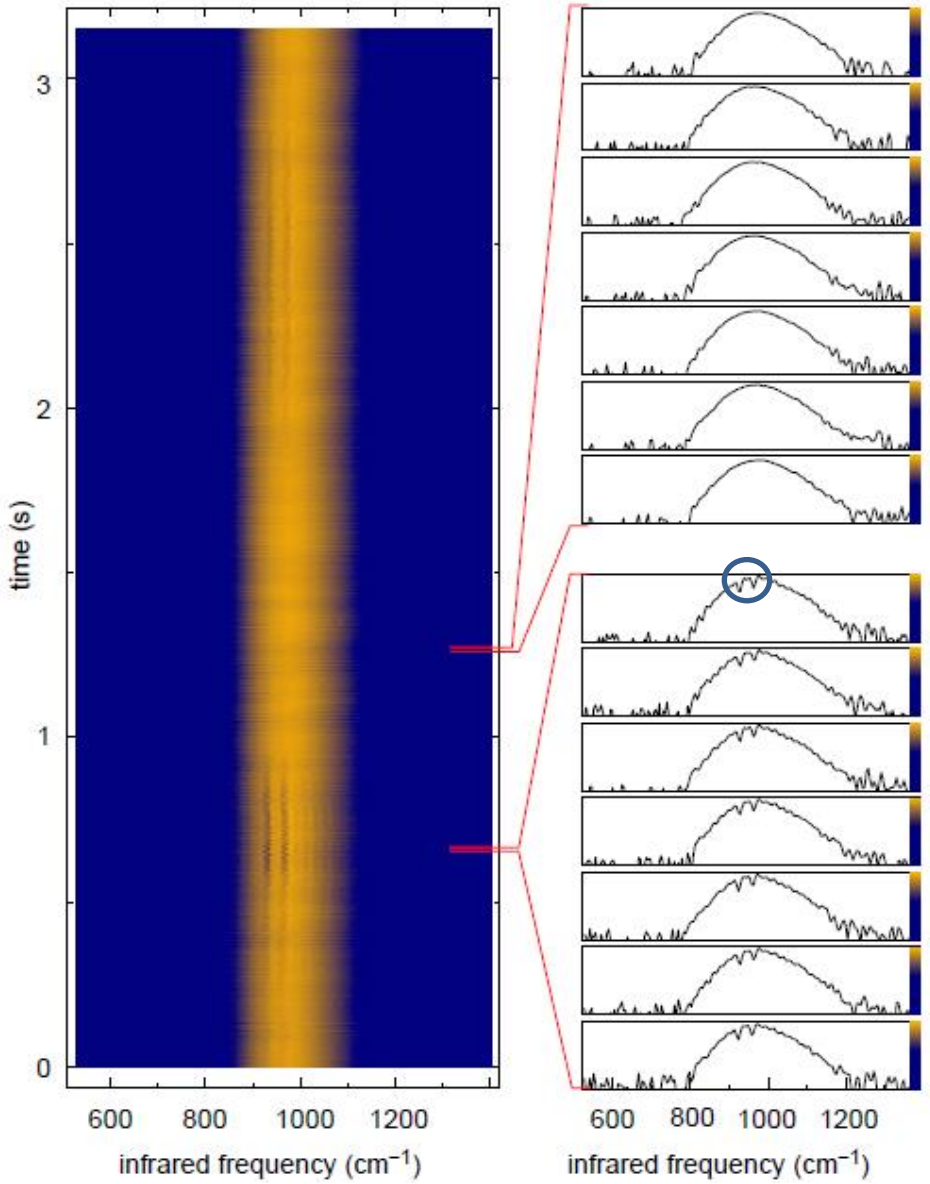


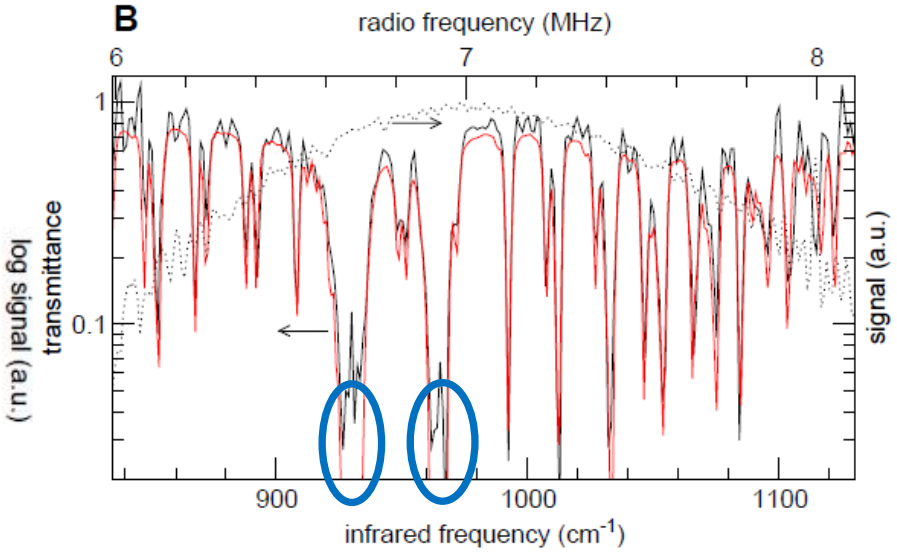
Only this part is obtained without wait time.

Setup for remote sensing



Result





3000 spectra

Record time = 3.15 s

Δ = 14 Hz to - 13.6 Hz

950 spectra / s

Summary

- 950 spectra repetition rate attained by manipulating the repetition rate of one laser.

- Signal dose not depend on propagation phase or mild beam deviation by turbulence.

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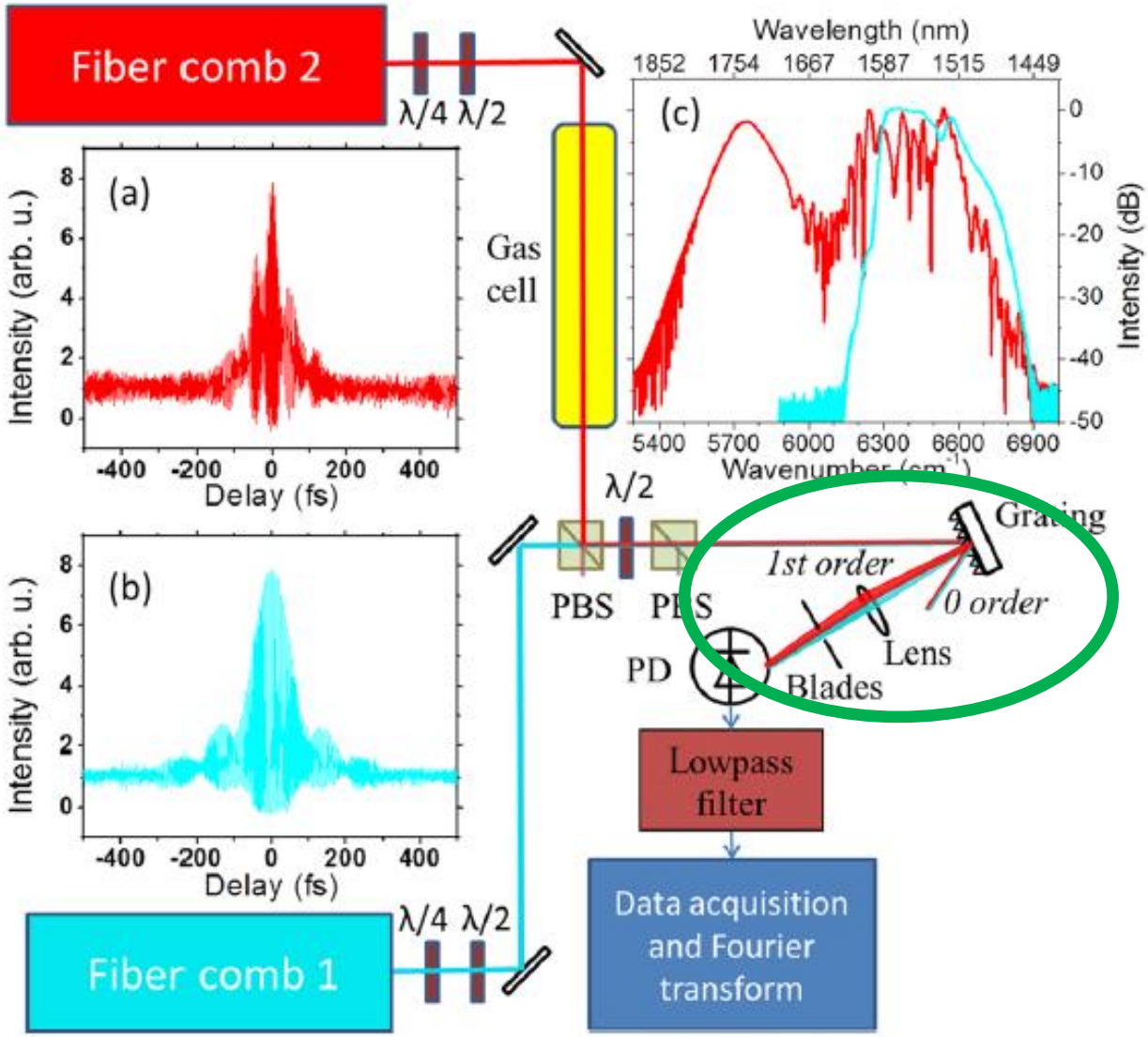
Setup

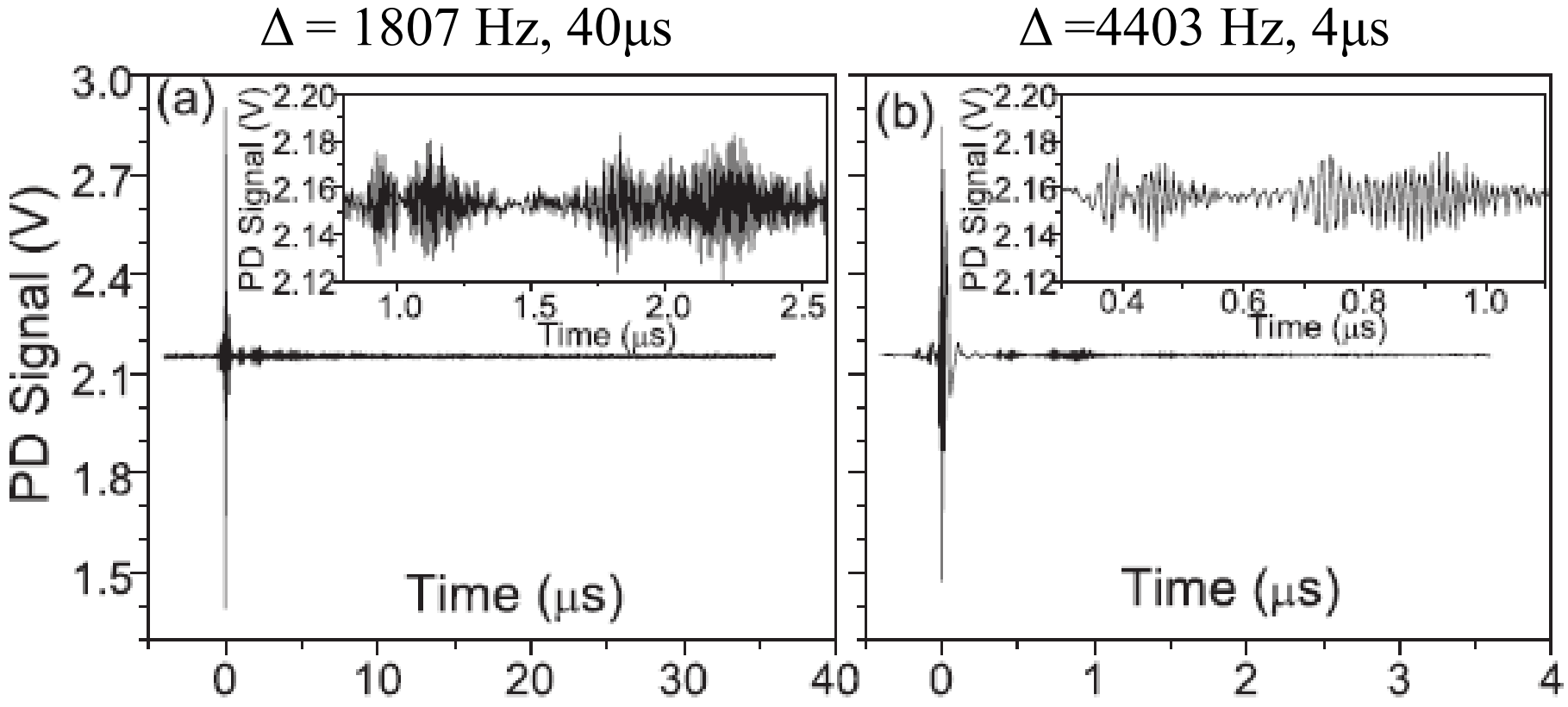


Comb1
Er-doped fiber laser
Power : 25 mW
Pulse width : 70 fs

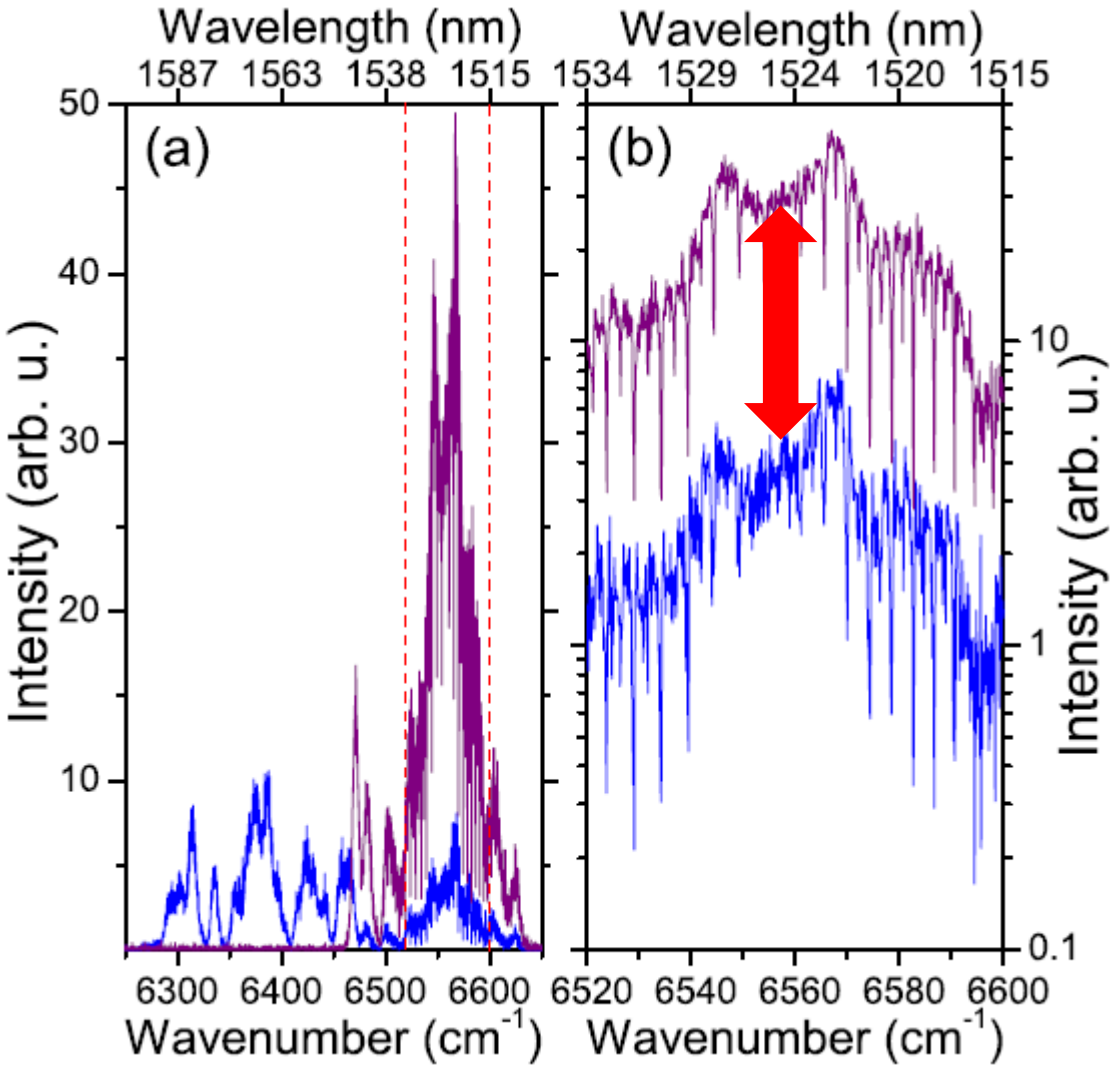
Comb2
Er-doped fiber amplifier
Power : 500 mW
Pulse width : 90 fs

・Repetition rate : 250 MHz is locked
・CEO frequencies are not stabilized

Interferogram



Fourier spectra



Blue : filtering between 6280 ~ 6625cm^{-1}

maroon : filtering between 6460 ~6625cm^{-1}

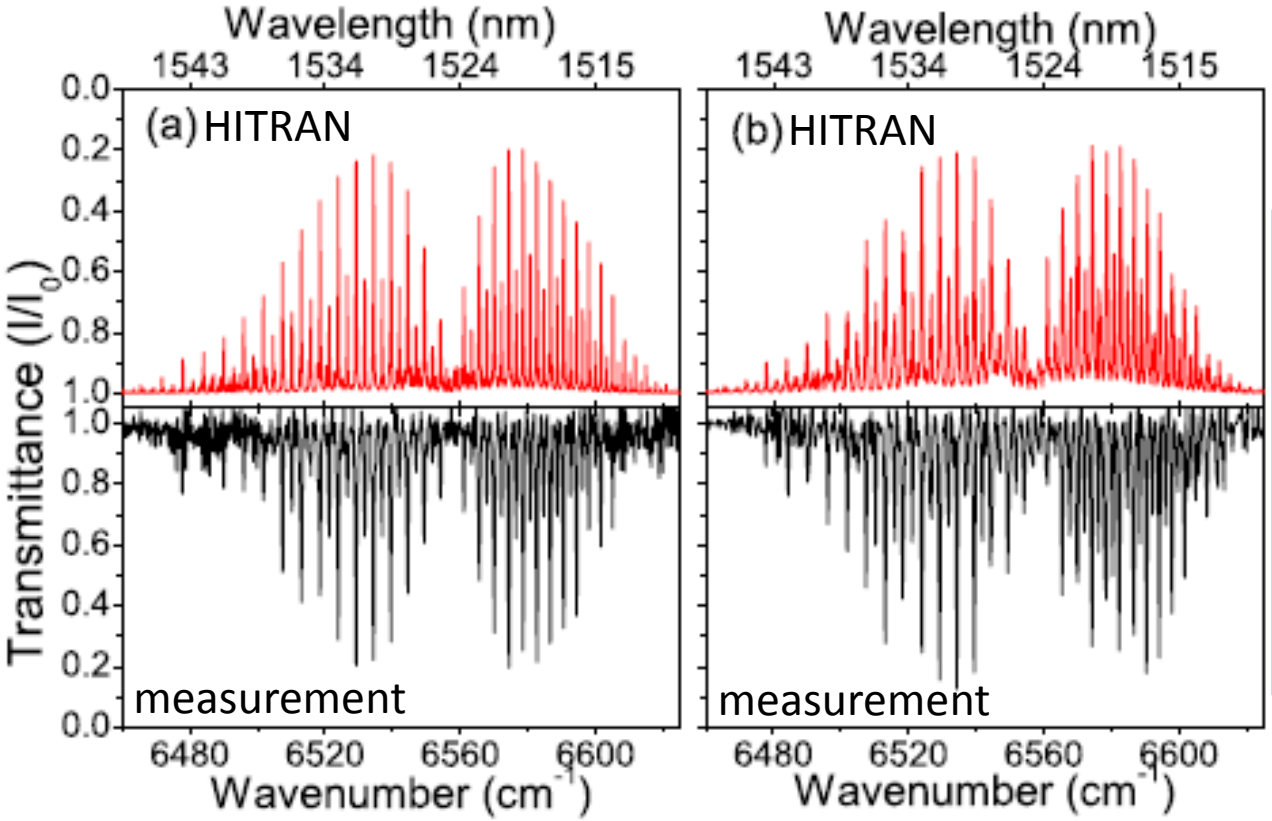
When selecting only the fingerprint spectral region, ~6 times stronger signal is obtain.

Rapid spectroscopy

40 µs interferogram,
Δ = 1807 Hz

4 µs interferogram,
Δ = 4403 Hz

$$resolution = \frac{1}{temporal\ window} \times \frac{f_1}{\Delta}$$



(a) :
Resolution : 0.11 cm^{-1}
Spectral elements : 1500
Most intensity line's SNR : 30
(b) :
Resolution : 0.47 cm^{-1}
Spectral elements : 351
Most intensity line's SNR : 80

Summary

- By used grating based spectral filter in a *2f-2f* setup, increased the signal to noise ratio.

- The difference between the repetition rates is 4403 Hz and measurement time is 4 µs.

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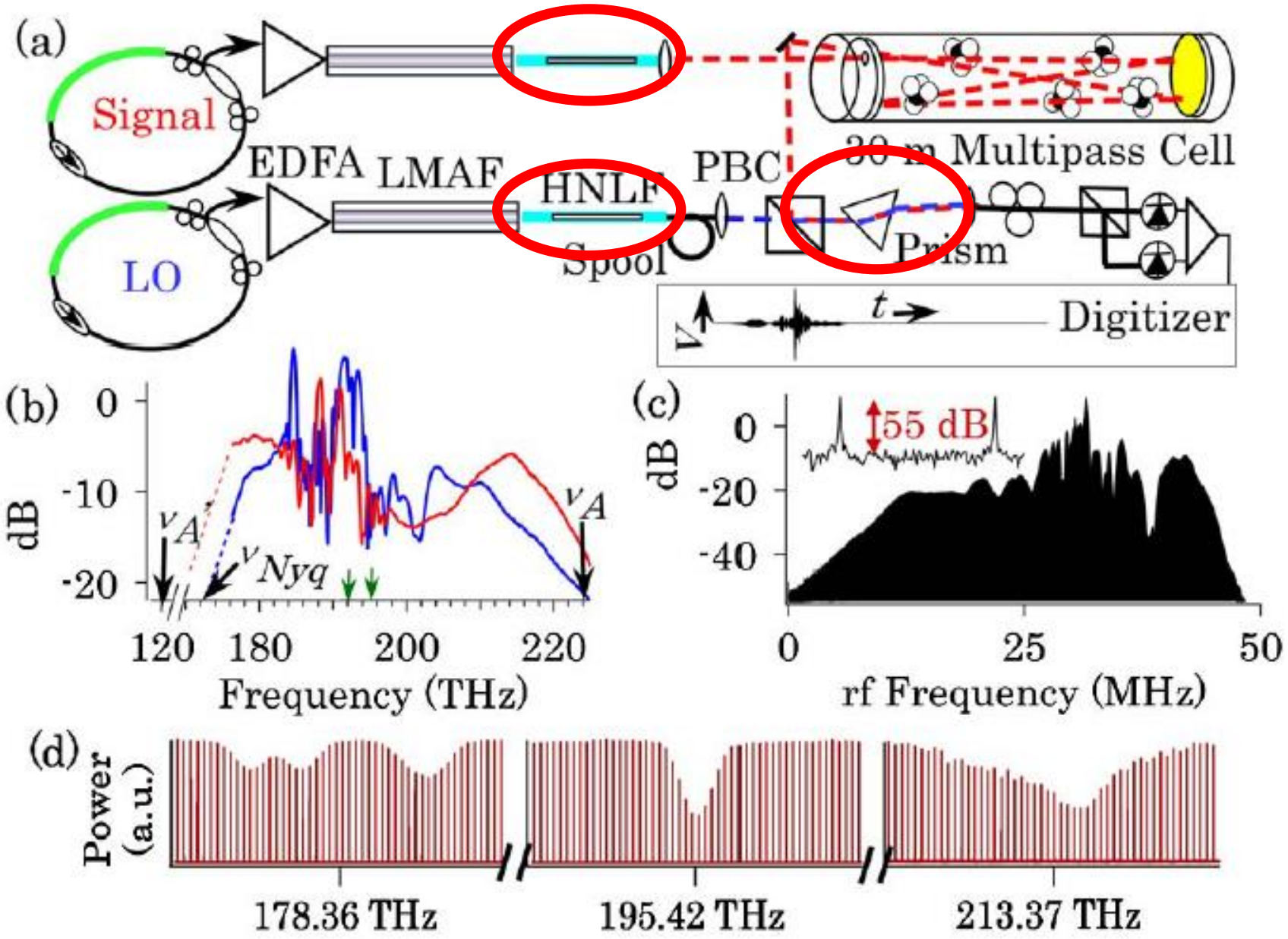
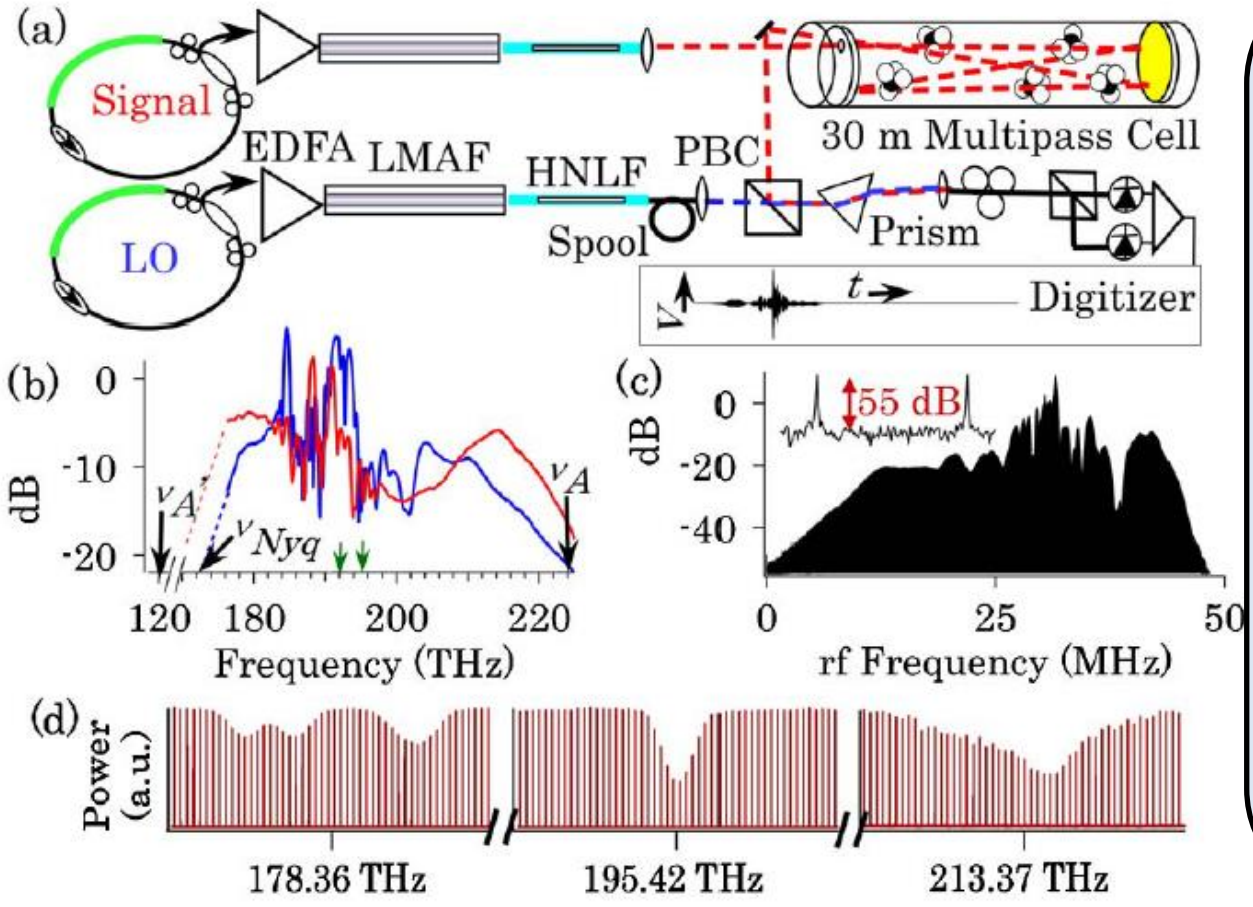
Setup


(a)
Signal
LO
EDFA
LMAF
HNLF
Spool
PBC
Multipass Cell
Prism
t
Digitizer
(b)
dB
0
-10
-20
ν_A
ν_{Nyq}
120
180
200
220
Frequency (THz)
(c)
dB
0
-20
-40
55 dB
0
25
50
rf Frequency (MHz)
(d)
Power (a.u.)
178.36 THz
195.42 THz
213.37 THz

Setup

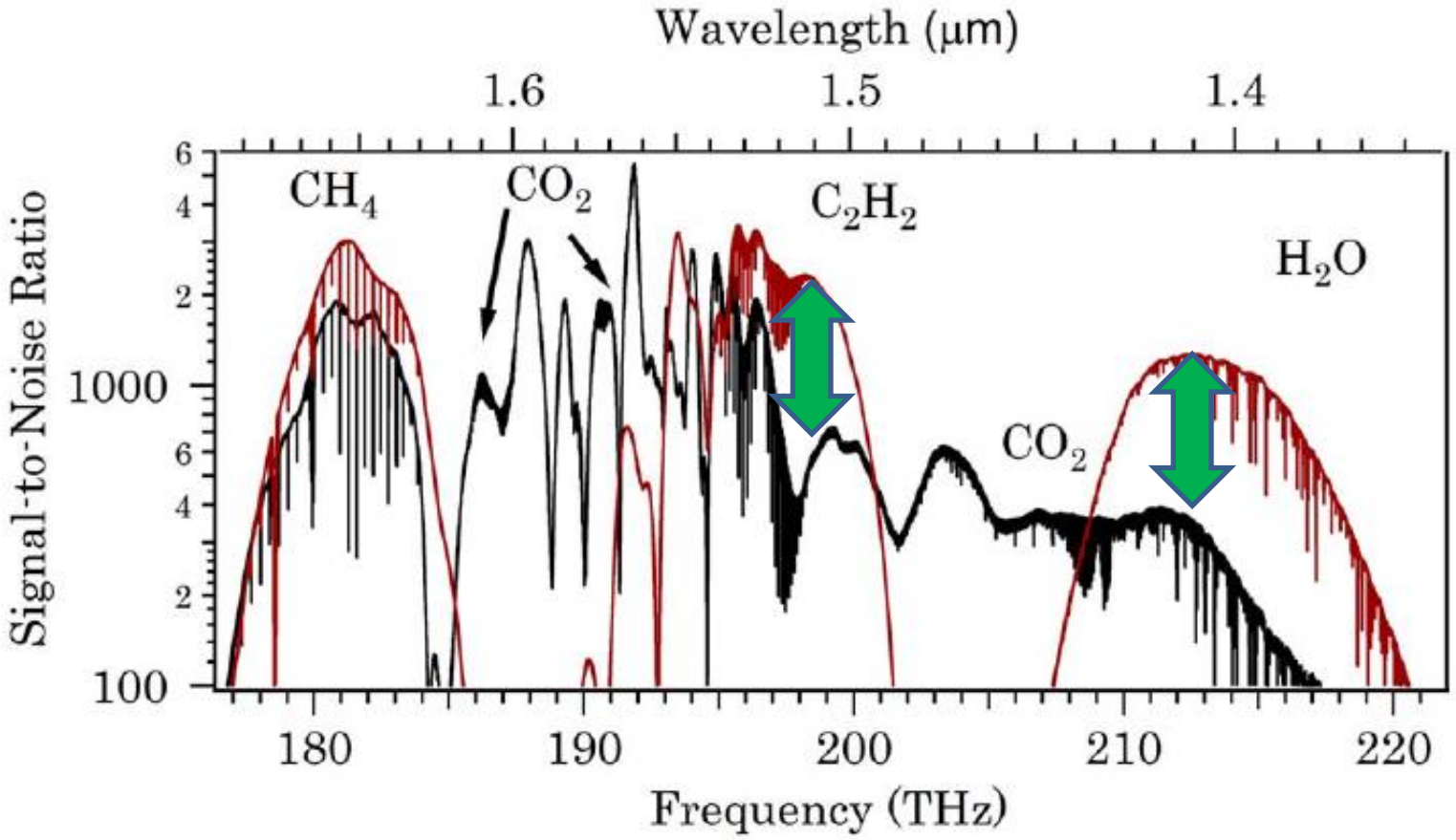


Signal comb, local comb
SC generated by HNLF
Power : ~300 mW
Bandwidth : ~43THz

Repetition rate : 100 MHz are locked.
CEO frequencies are stabilized.

Δ = 100 Hz

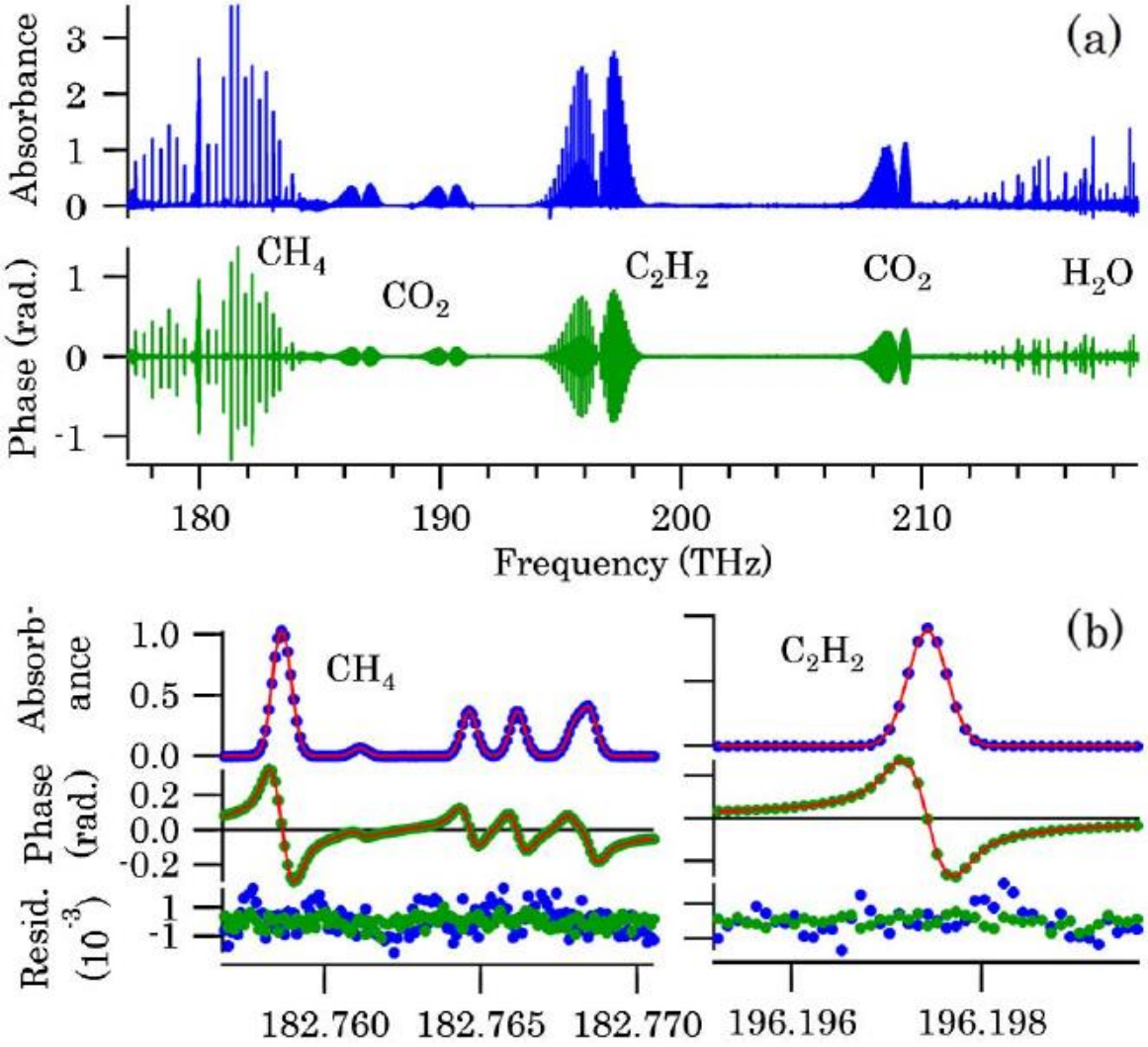
Multiple species spectroscopy



Black : full region of SC
SNR > 100
Phase noise : 0.01 rad
Absorbance noise : 0.02

Red : prism-filtered spectra
SNR > 3000
Phase noise : 330 µrad
Absorbance noise : $6.6*10^{-4}$

Evaluate the accuracy



Line centers agree to within the ~10 MHz .

Measurements data(symbols) is coincides Doppler-limiter line(solid line) .

Summary

- Dual comb spectroscopy can probe multiple species of interest simultaneously over 43 THz.

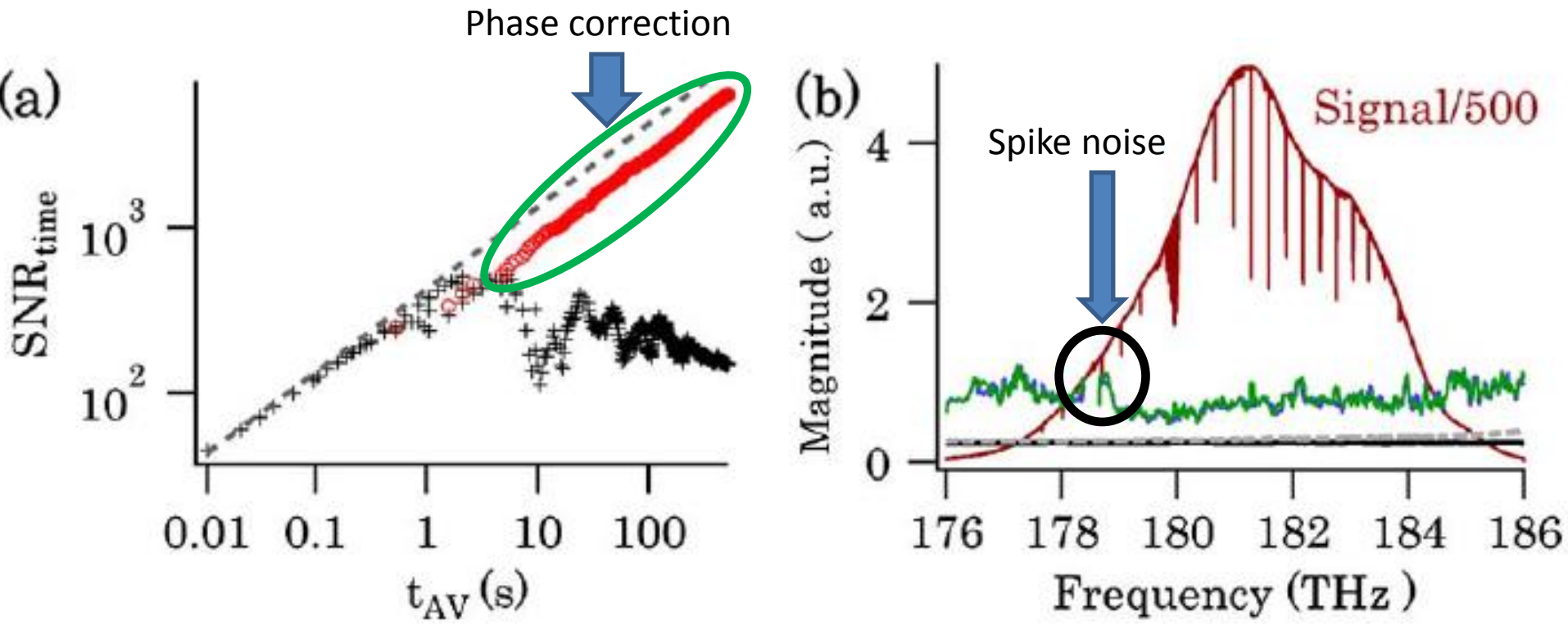
- Or select a subset of the bandwidth for increased SNR.

Conclusion

- High signal to noise ratio dual comb spectroscopy is attained by prism-filtering or by grating filtering.

- By changing the repetition rate, 950 spectra/s attained.

SNR of interferogram and spectra



Time-domain SNR with linear phase correction is increases as $t^{1/2}$.