



# 107° CONGRESSO NAZIONALE della SOCIETÀ ITALIANA DI FISICA



## High-resolution direct-comb spectrometer at 2.4 $\mu$ m

Edoardo Vicentini, Andrea Rosina, Mauro Nobis, Francesco Canella, Yuchen Wang, Paolo Laporta and Gianluca Galzerano



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## High-resolution direct-comb spectrometer at 2.4 $\mu$ m

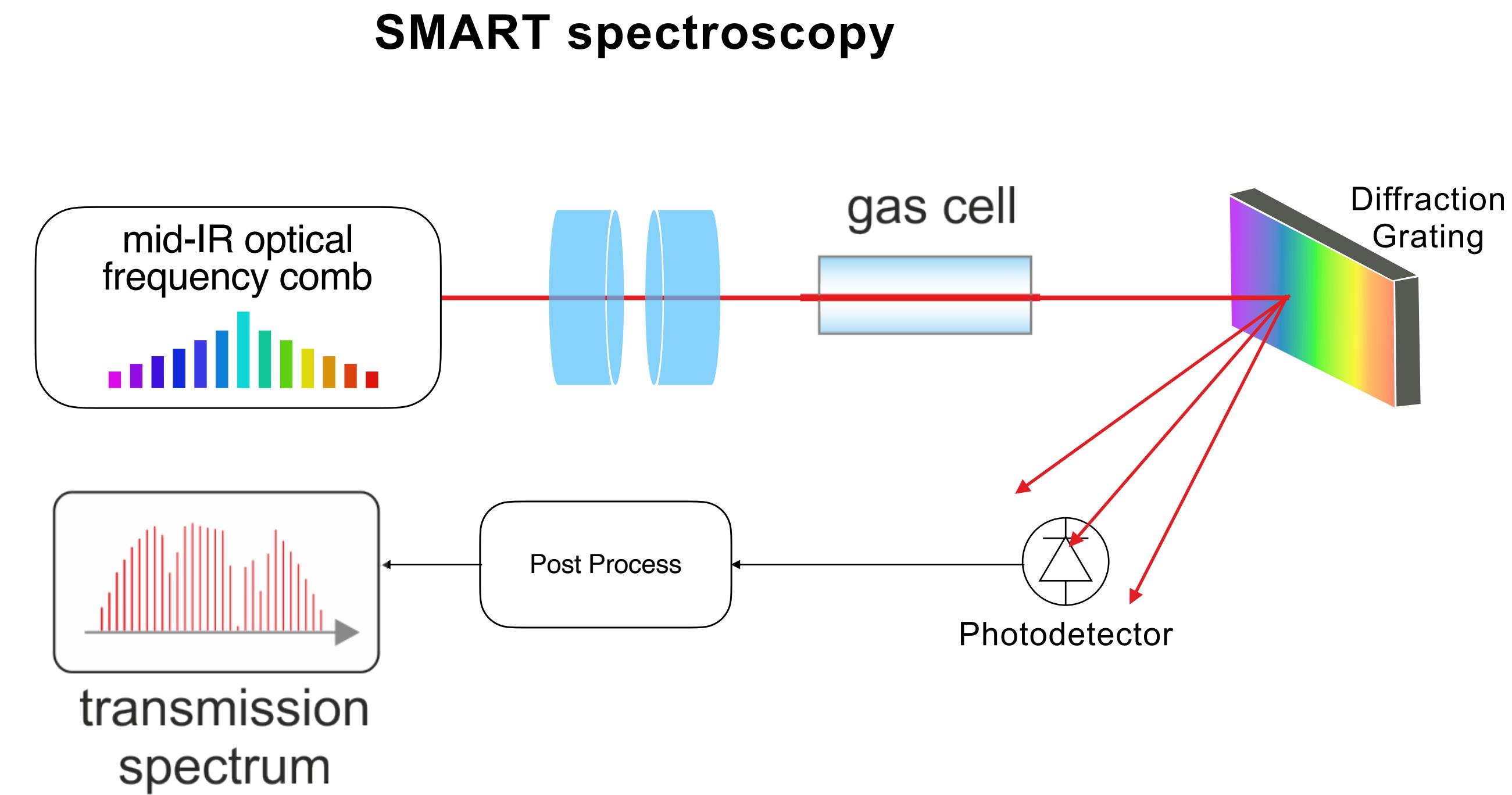
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# Novelty

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## Novelty

- First high resolution spectroscopy with mid-infrared solid-state optical frequency comb
- SMART versatile and compact



# Outline

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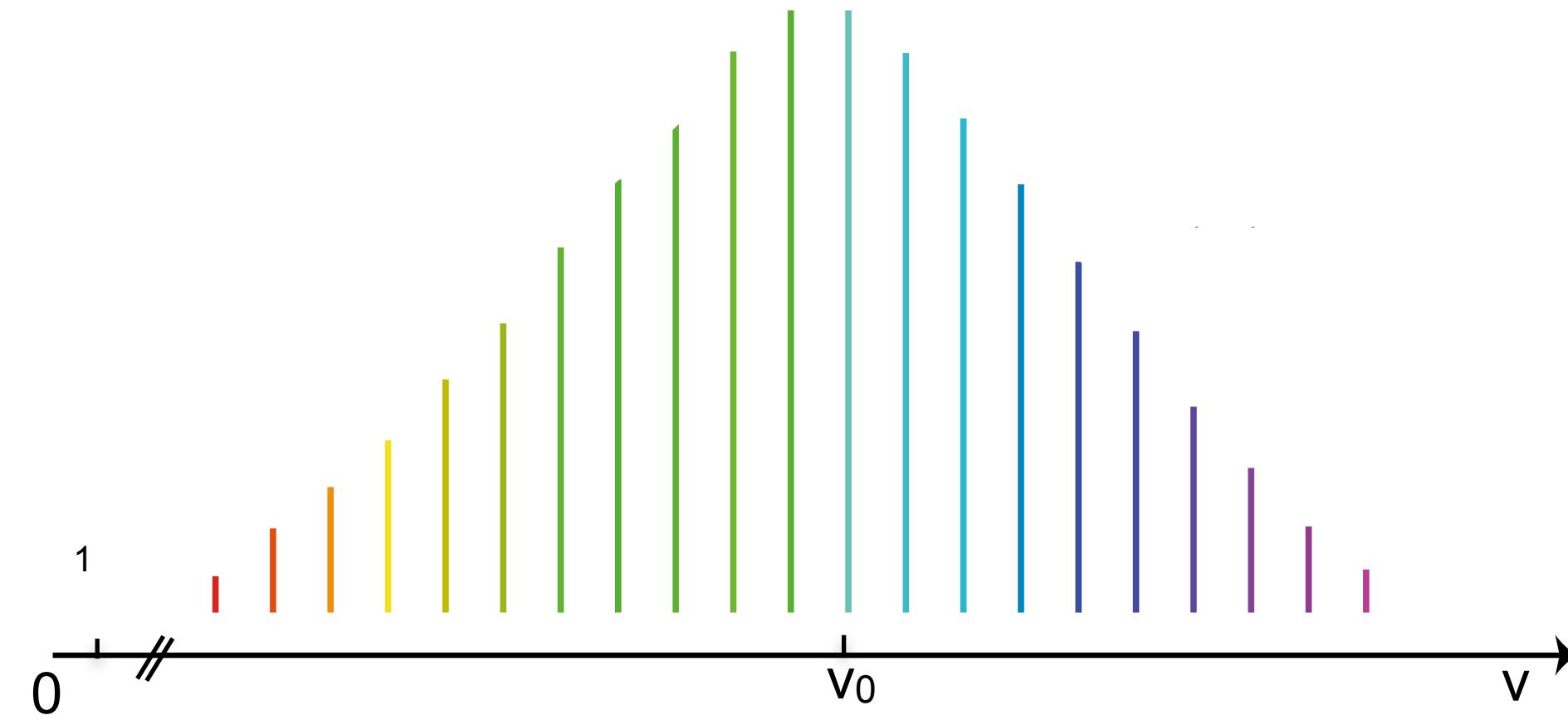
- **Introduction**
  - Optical frequency comb
- **SMART spectrometer at  $2.4 \mu\text{m}$** 
  - Experimental setup
  - Experimental result
- **Conclusion and future developments**



# Optical Frequency Comb

- Frequency domain

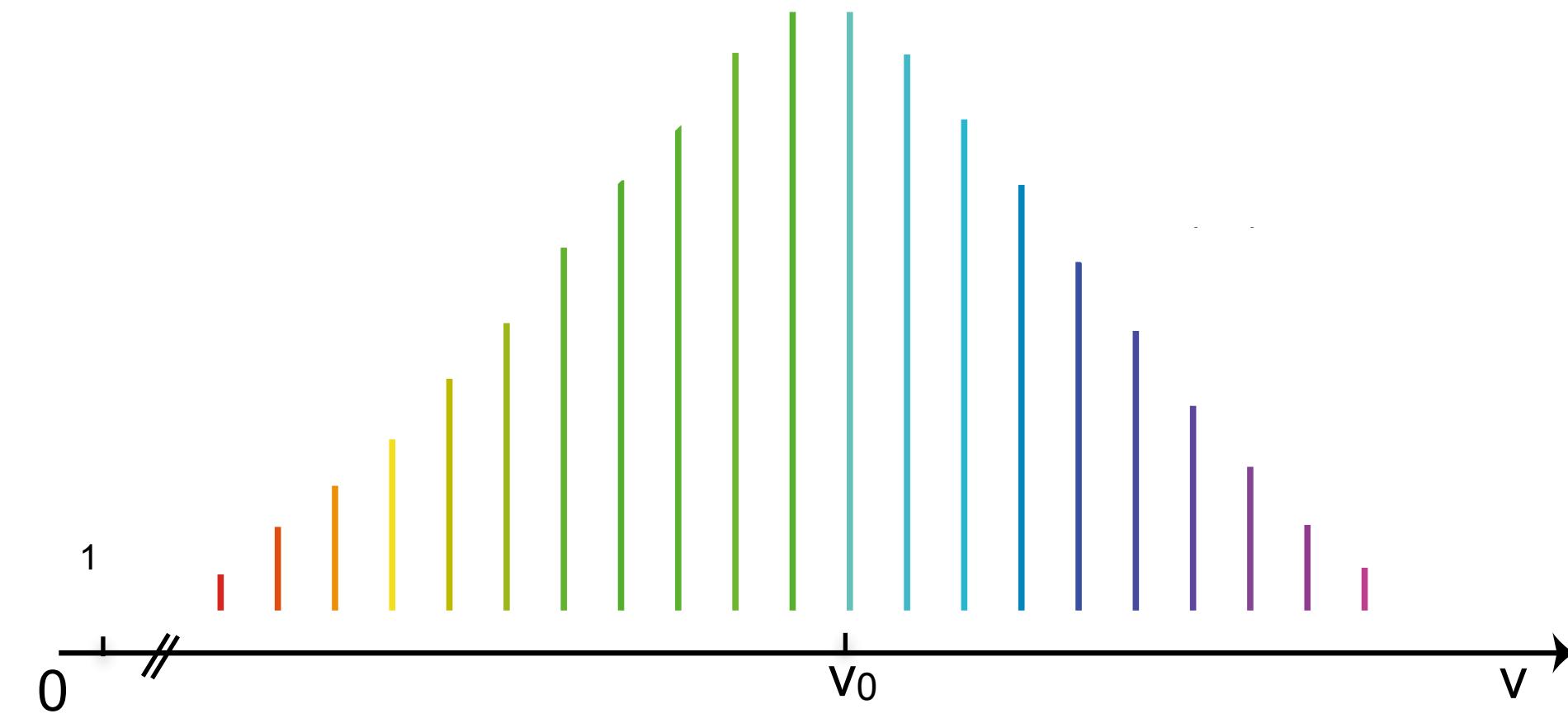
Thousand of CW lasers equally spaced



# Optical Frequency Comb

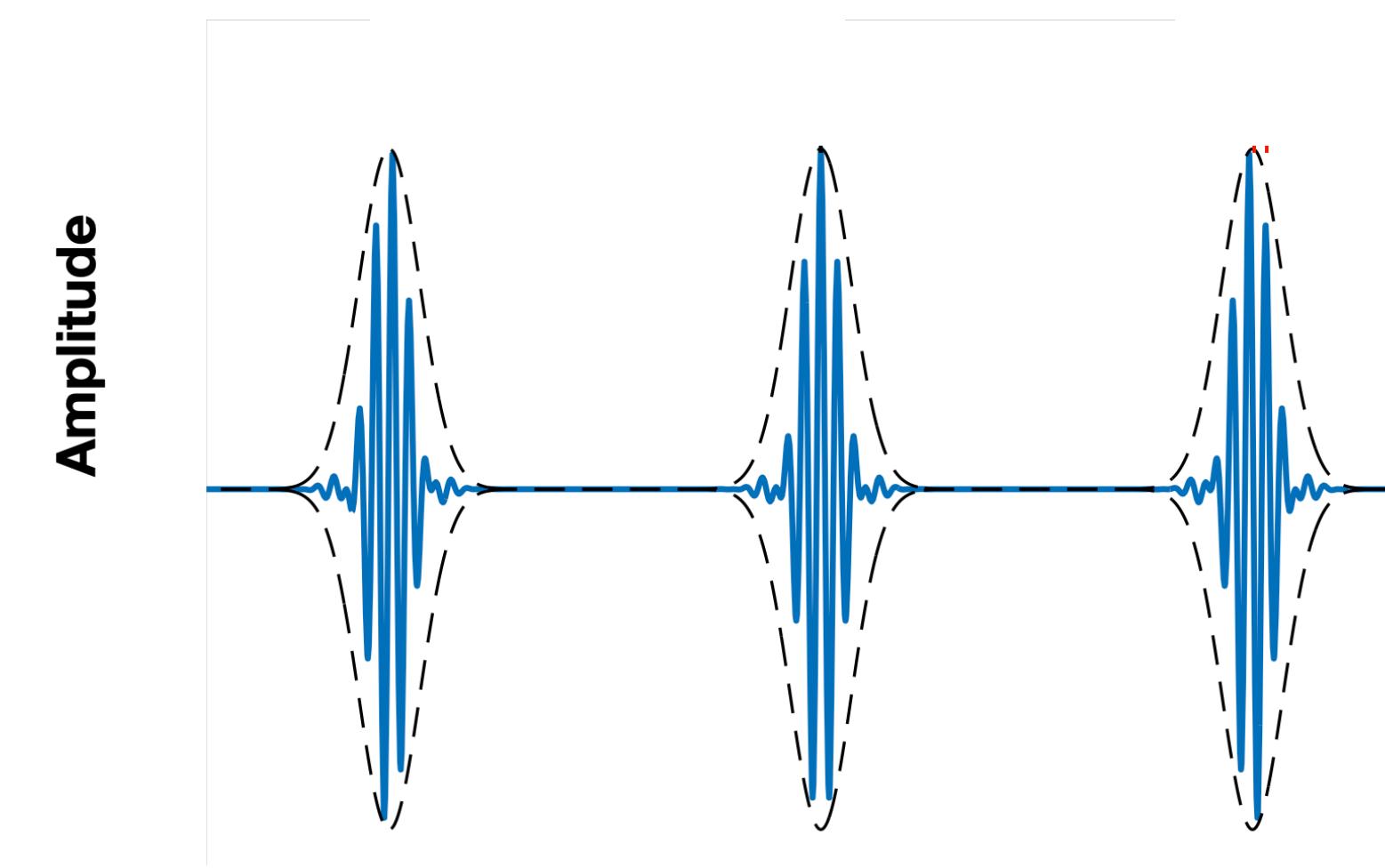
- **Frequency domain**

Thousand of CW lasers equally spaced



- **Time domain**

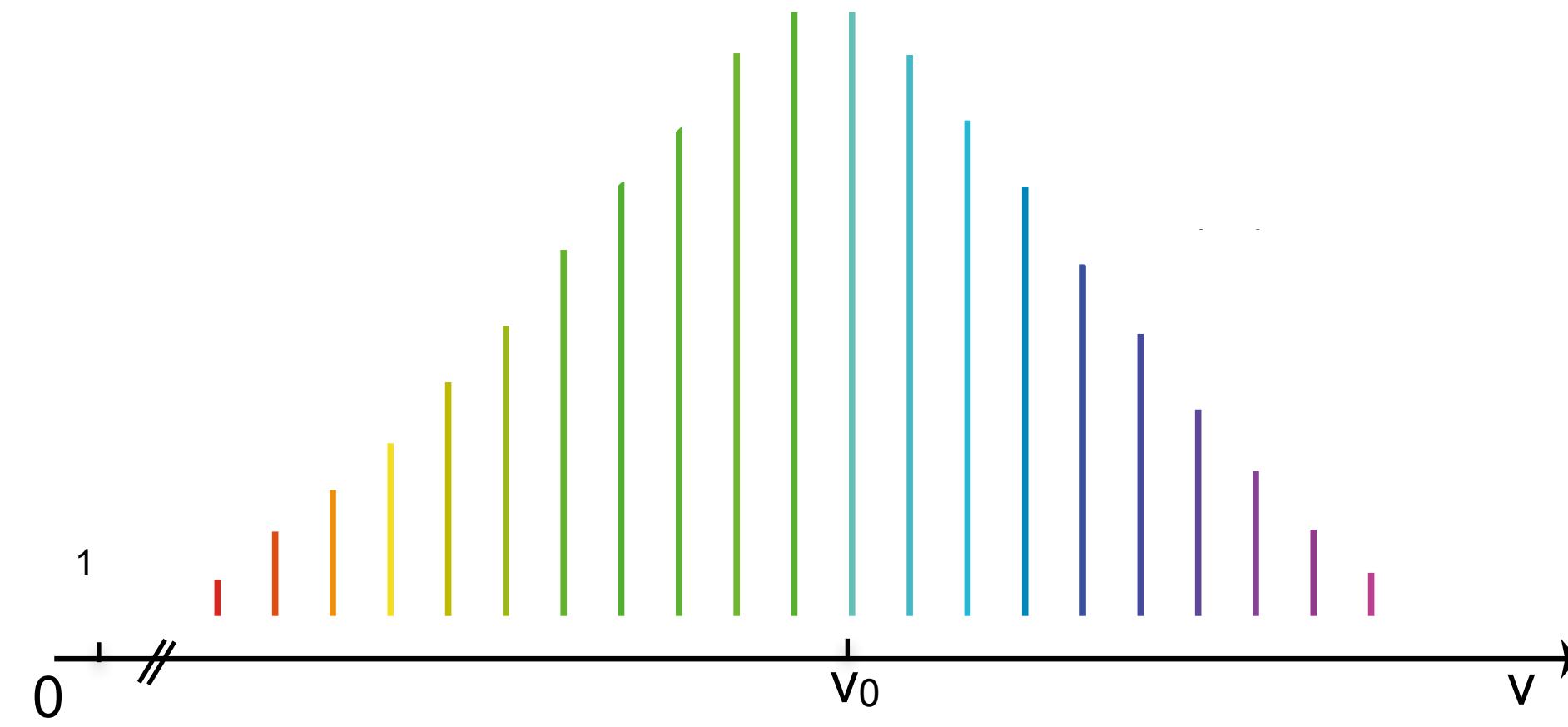
Stabilized train of pulses.



# Optical Frequency Comb

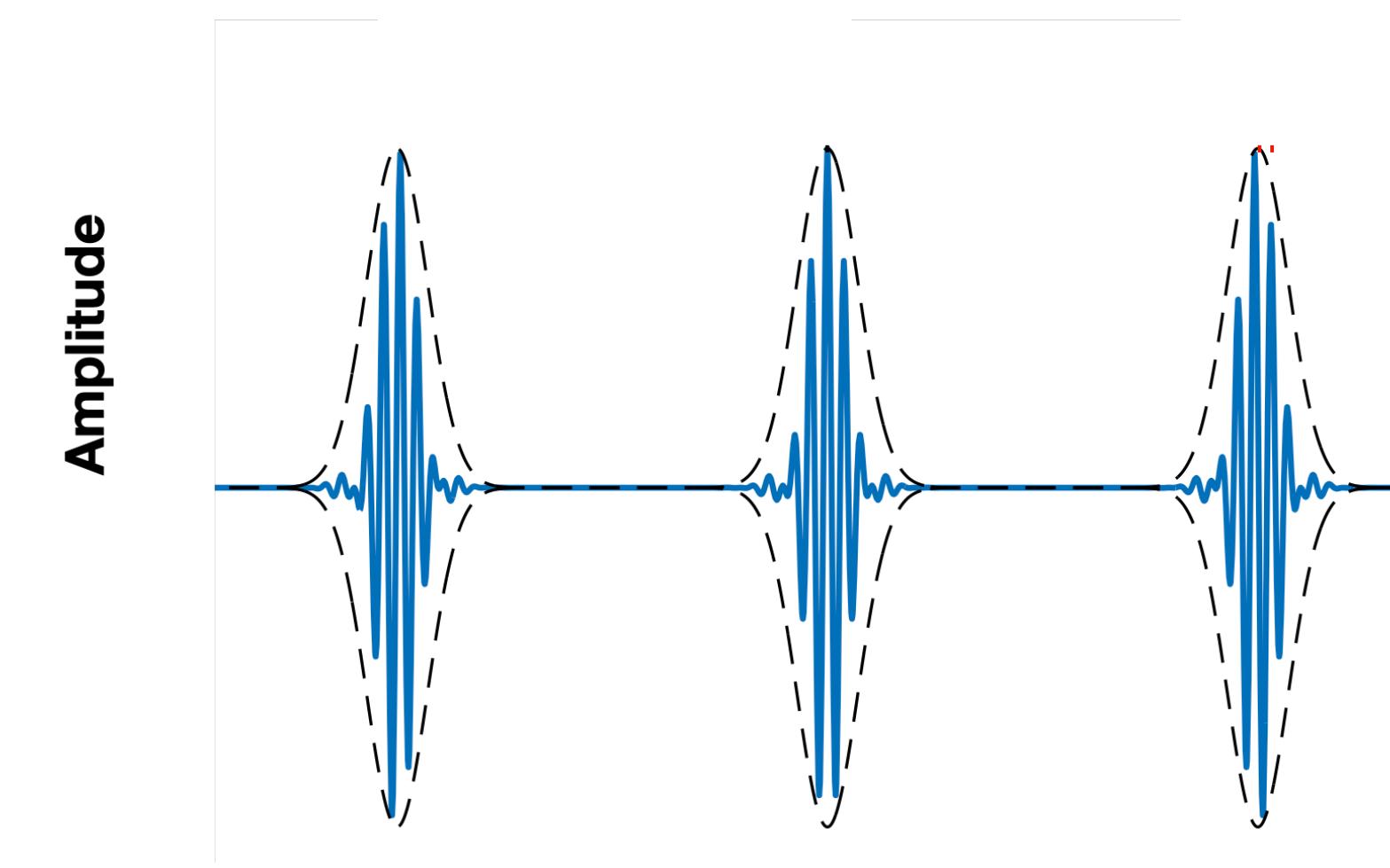
- **Frequency domain**

Thousand of CW lasers equally spaced



- **Time domain**

Stabilized train of pulses.

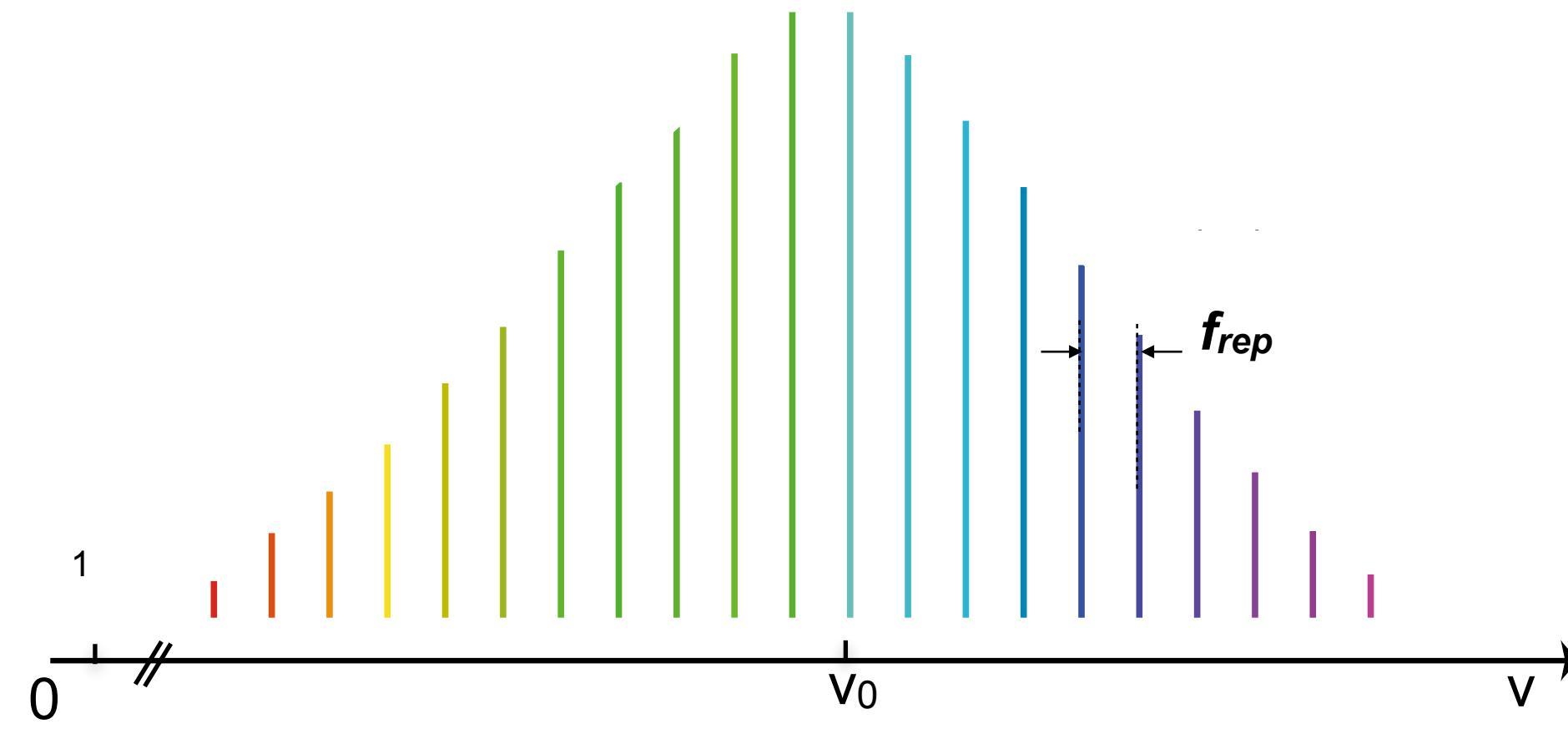


Frequency comb required stabilization of two quantities

# Optical Frequency Comb

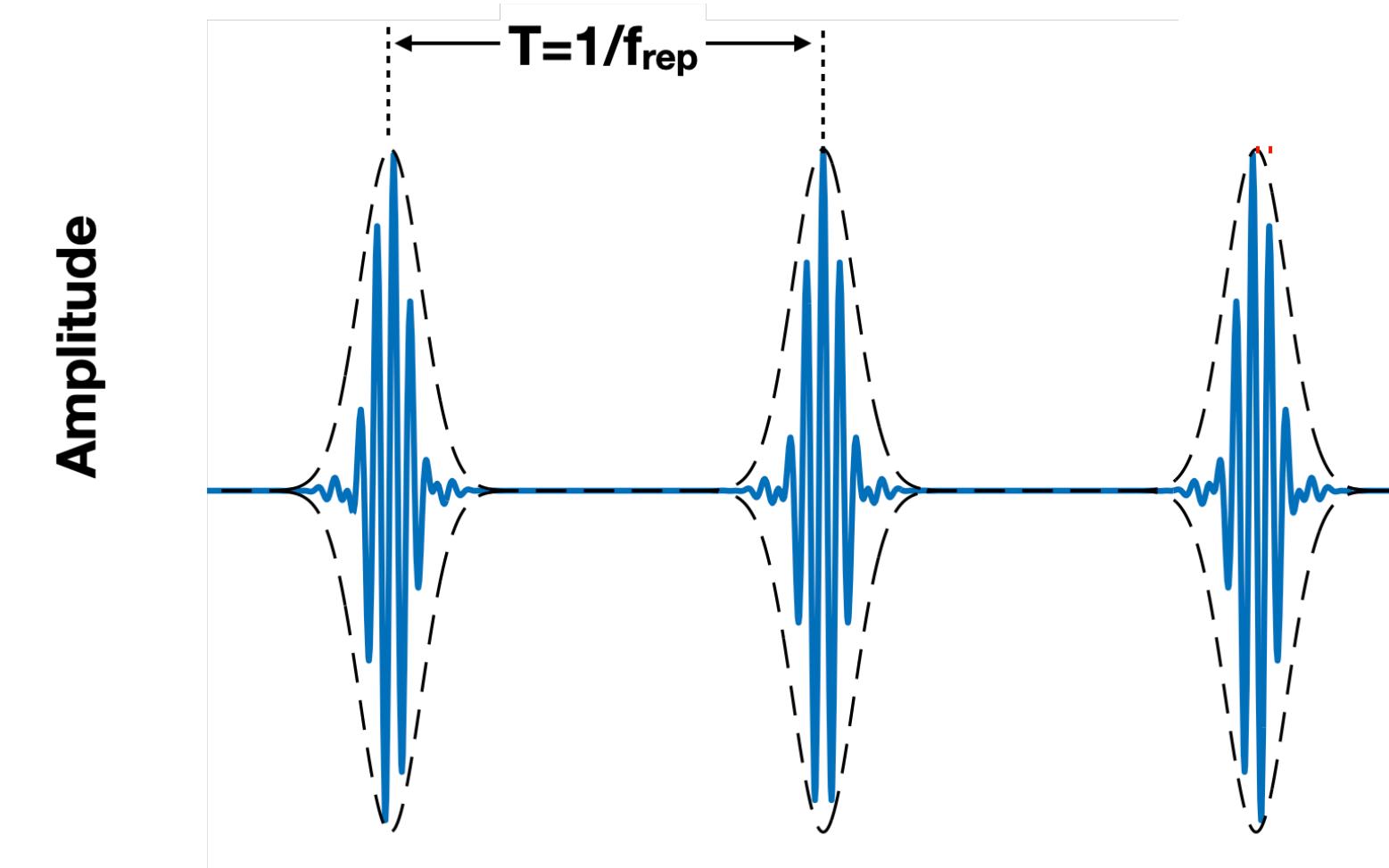
- Frequency domain

Thousand of CW lasers equally spaced



- Time domain

Stabilized train of pulses.



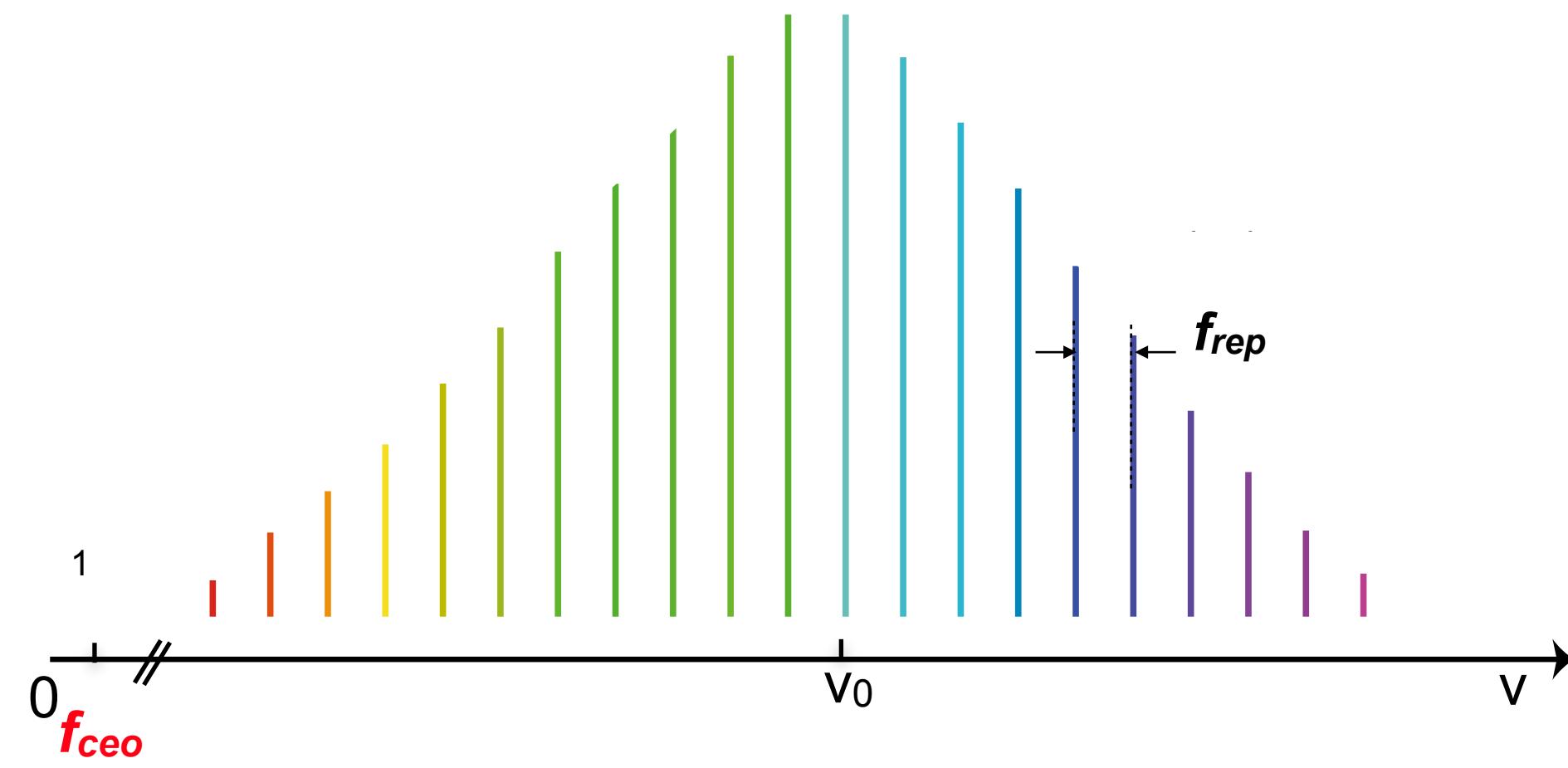
Frequency comb required stabilization of two quantities

- Repetition frequency of the pulses  $f_{rep}$

# Optical Frequency Comb

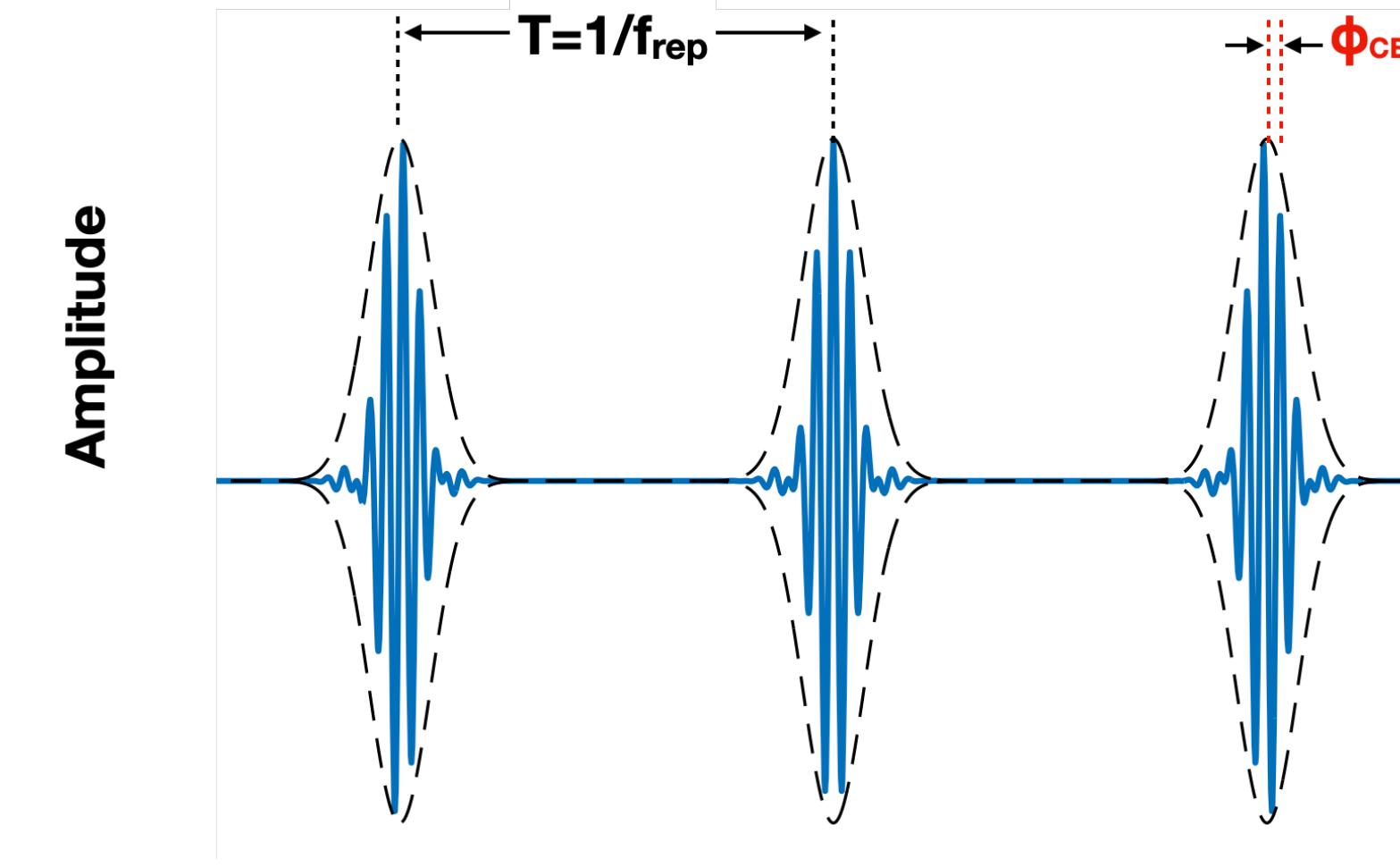
- Frequency domain

Thousand of CW lasers equally spaced



- Time domain

Stabilized train of pulses.



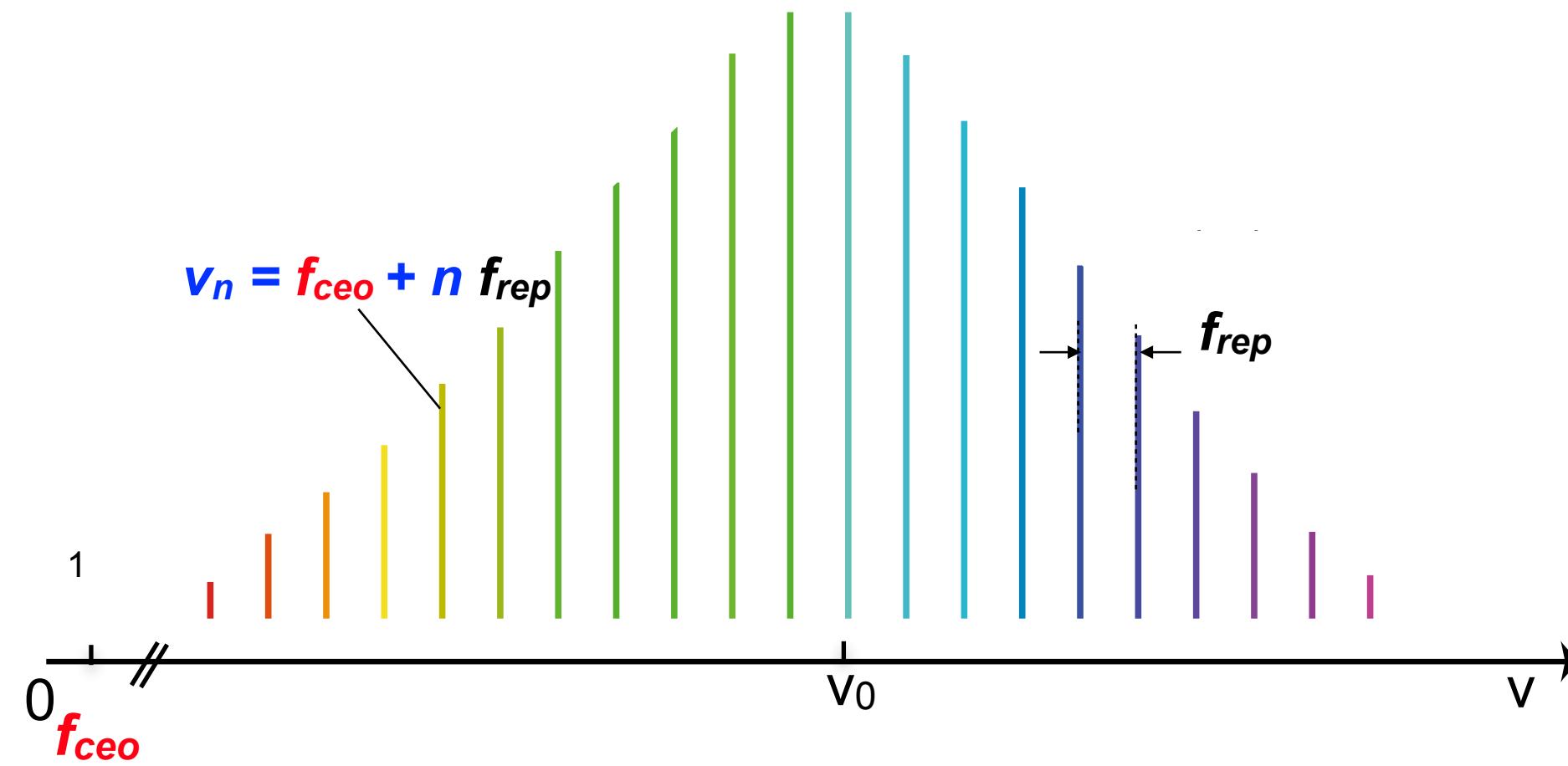
Frequency comb required stabilization of two quantities

- Repetition frequency of the pulses  $f_{rep}$
- Carrier-envelop offset frequency  $f_{ceo}$

# Optical Frequency Comb

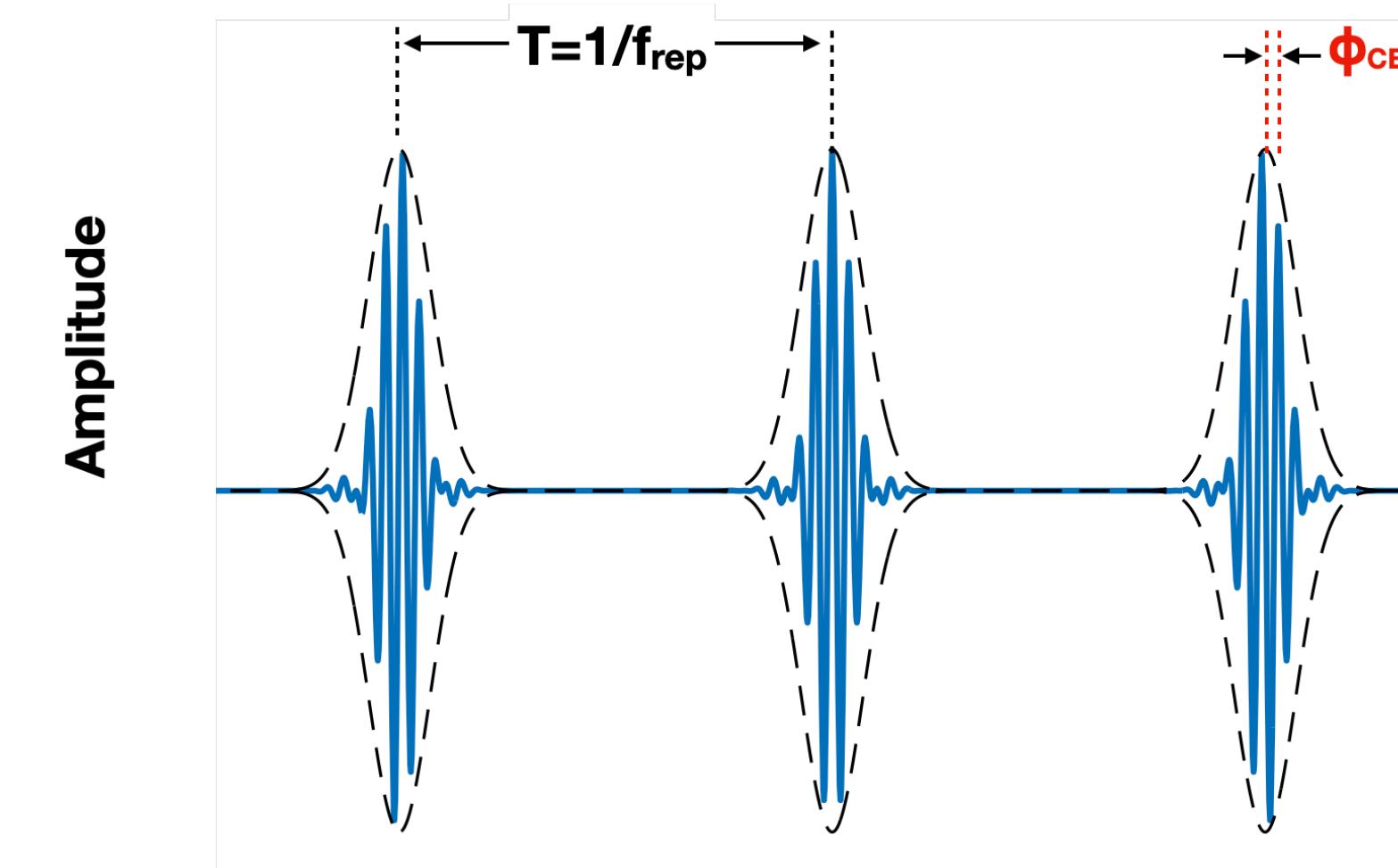
- Frequency domain

Thousand of CW lasers equally spaced



- Time domain

Stabilized train of pulses.



Frequency comb required stabilization of two quantities

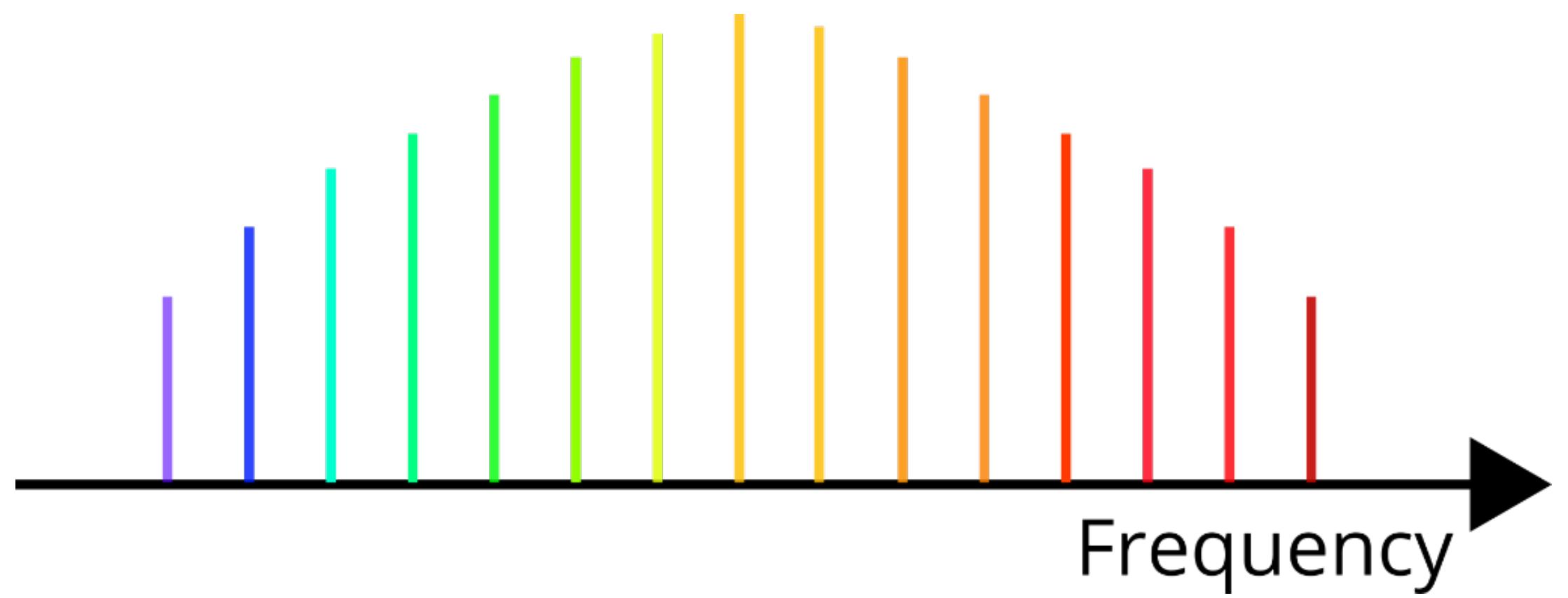
- Repetition frequency of the pulses  $f_{rep}$
- Carrier-envelop offset frequency  $f_{ceo}$

Once that these quantities have been stabilize every comb mode can be express

$$v_n = f_{ceo} + n f_{rep}$$

# Optical Frequency Comb

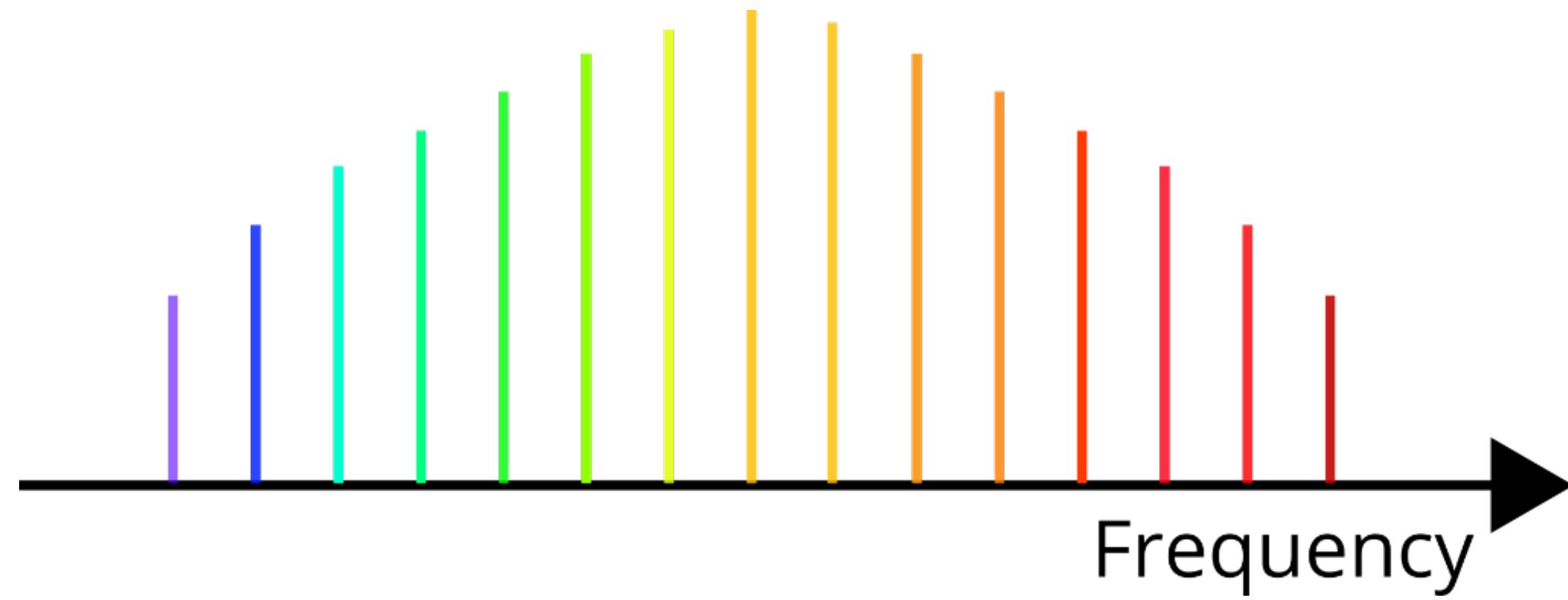
# Optical Frequency Comb



## Property

- Broad bandwidth
- Small linewidth
- Precise frequency of each line

# Optical Frequency Comb



## Property

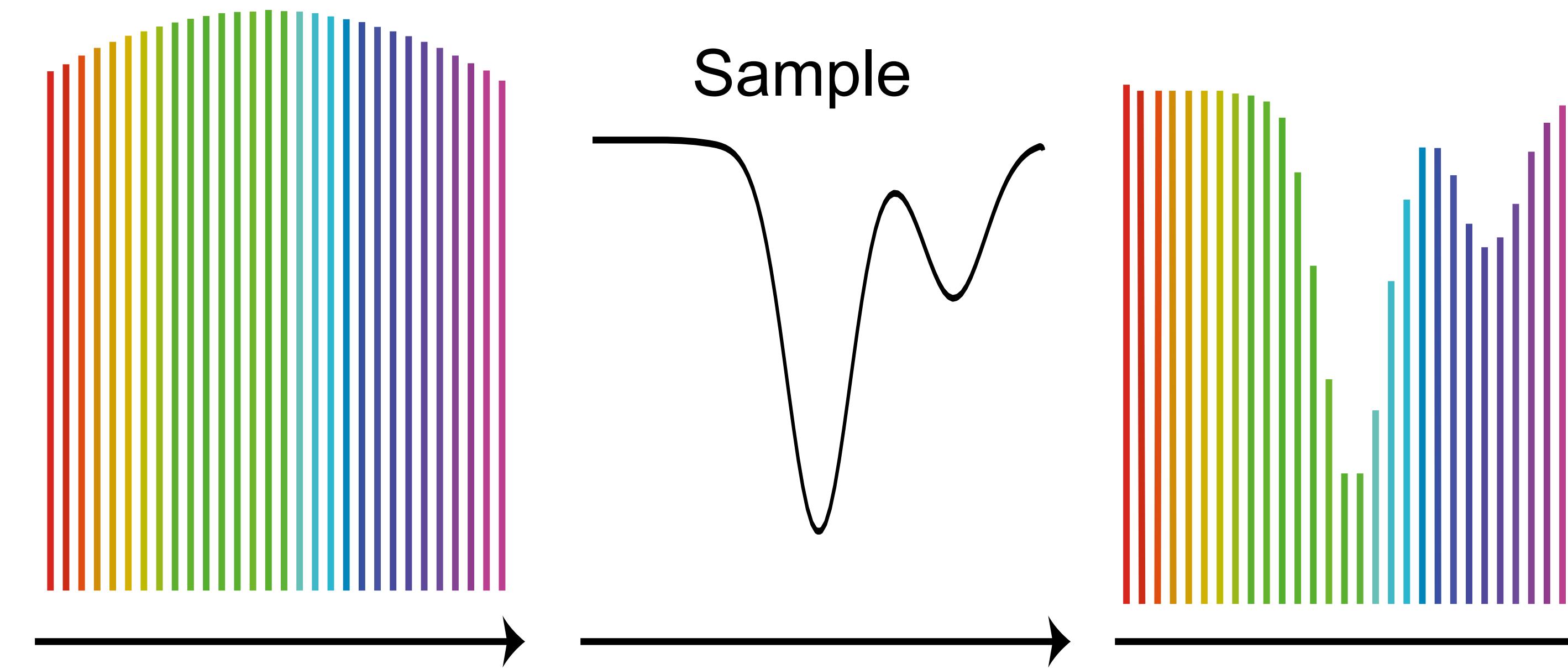
- Broad bandwidth
- Small linewidth
- Precise frequency of each line

## Application

- Precision spectroscopy
- Multi-species gas sensing
- Astrophysics calibration
- Fundamental physic testing
- Optical clock
- Lidar and ranging
- Holography
- ...

# Direct - Frequency comb spectroscopy

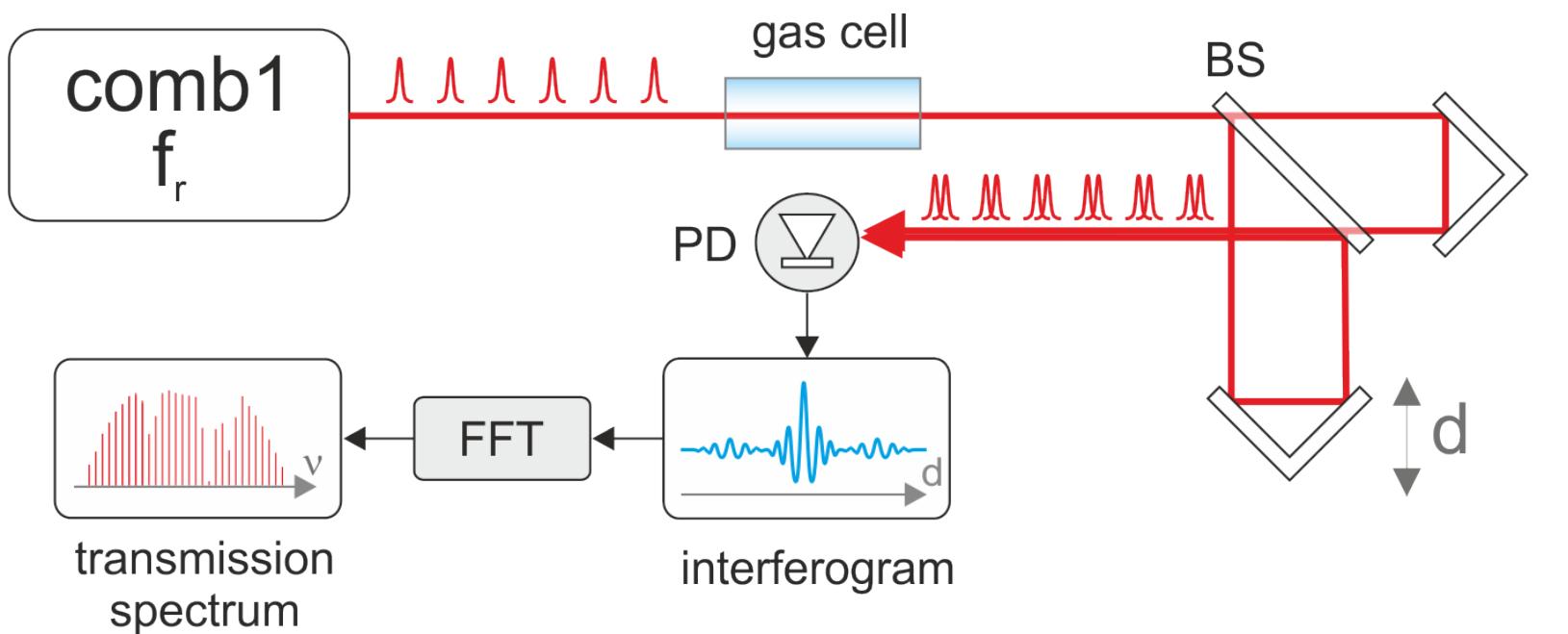
## Direct - Frequency comb spectroscopy



# Direct - Frequency comb spectroscopy

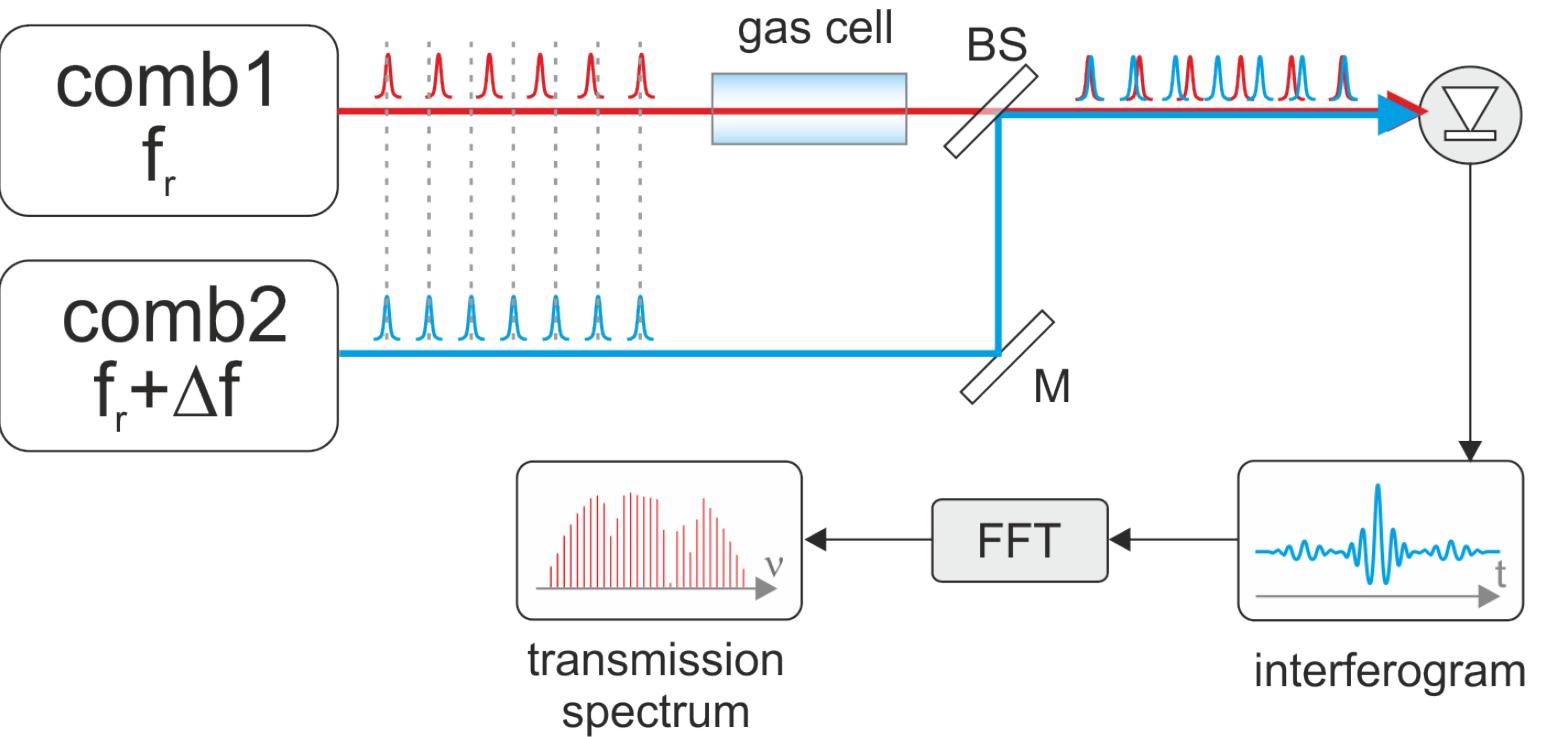
## Interferometric methods

- Fourier Transform (FTIR)



J. Mandon, et al. Nat. Photon. **3**, 99–102(2009)

- Dual Comb spectroscopy

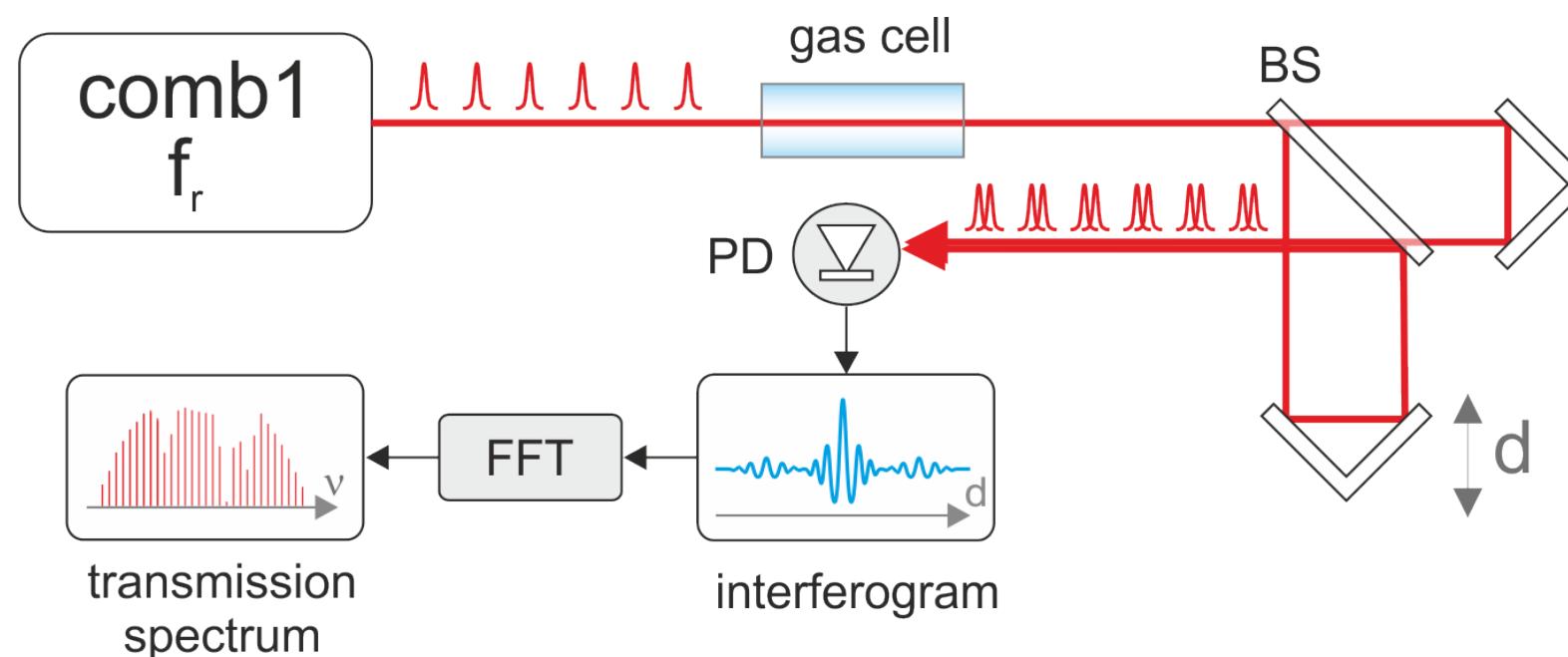


F. Keilmann, et al. Opt. Lett. **29**, 1542 (2004)

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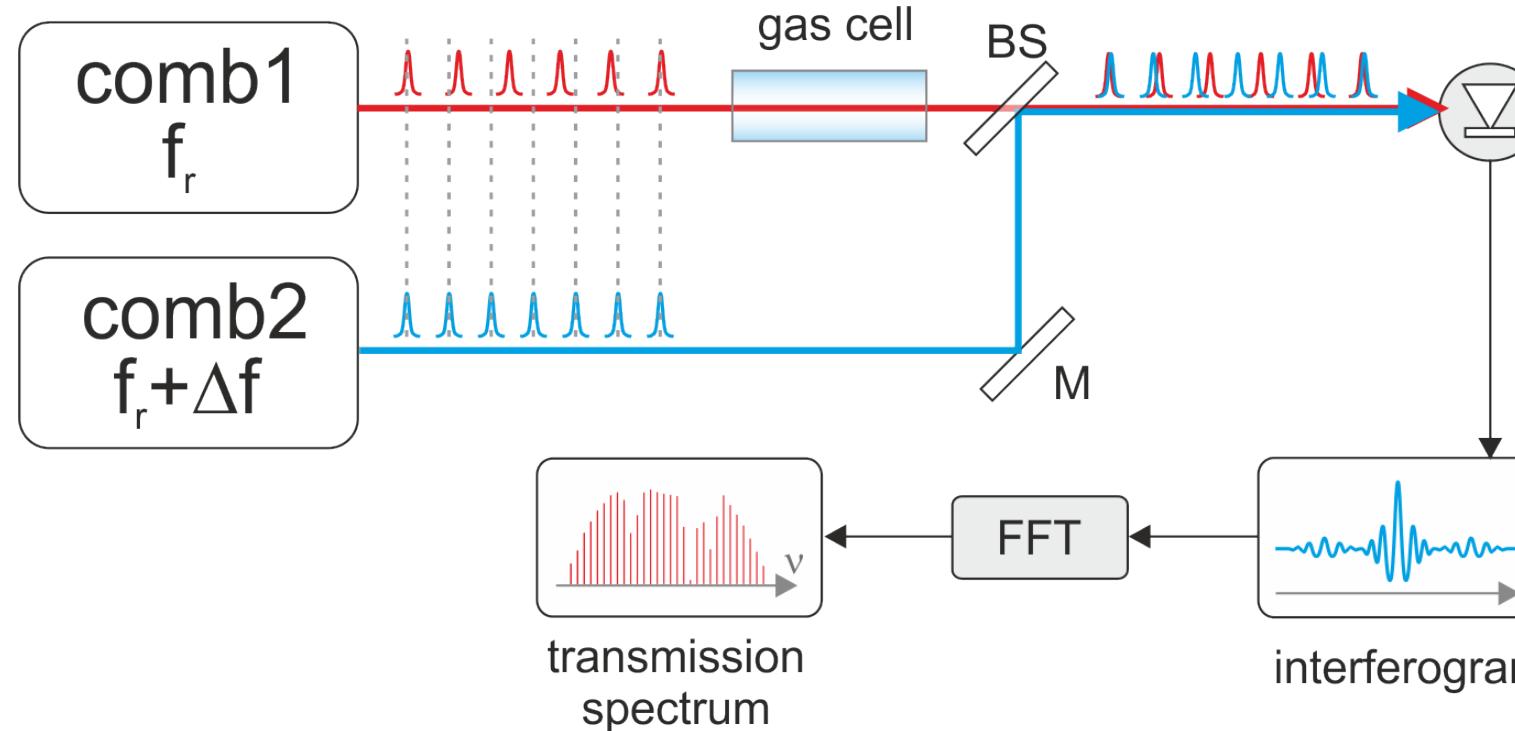
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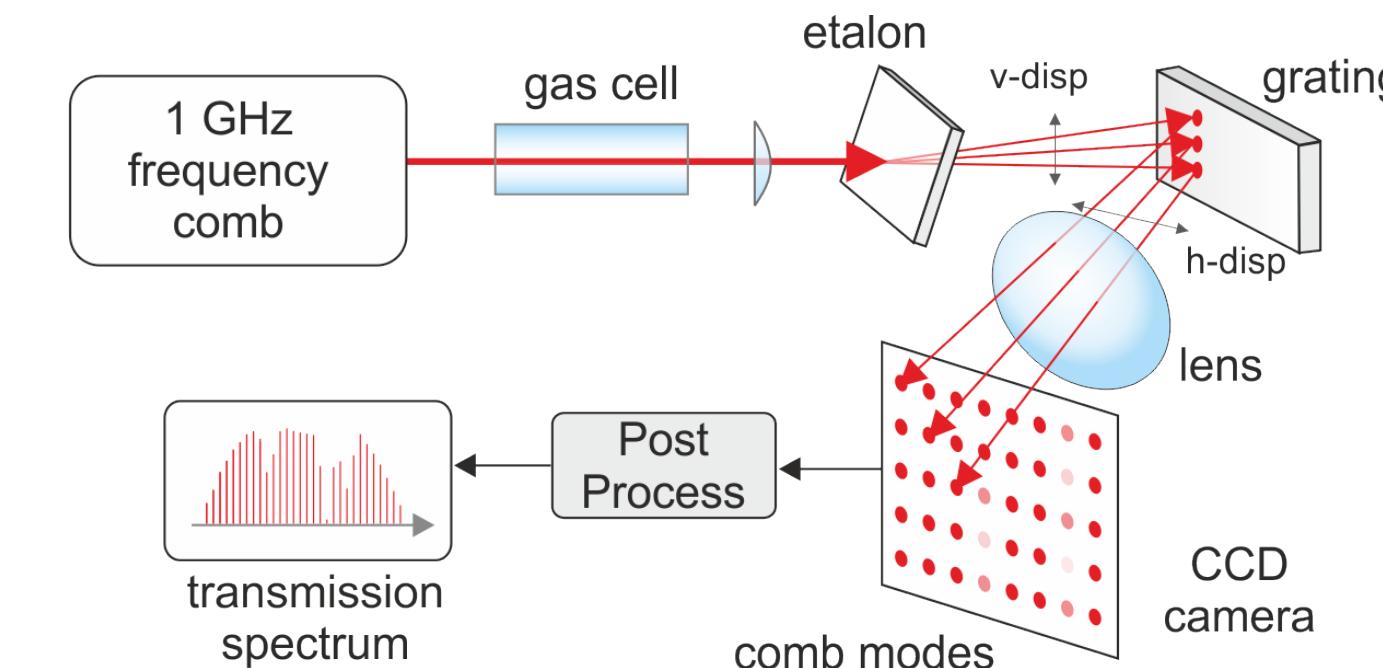
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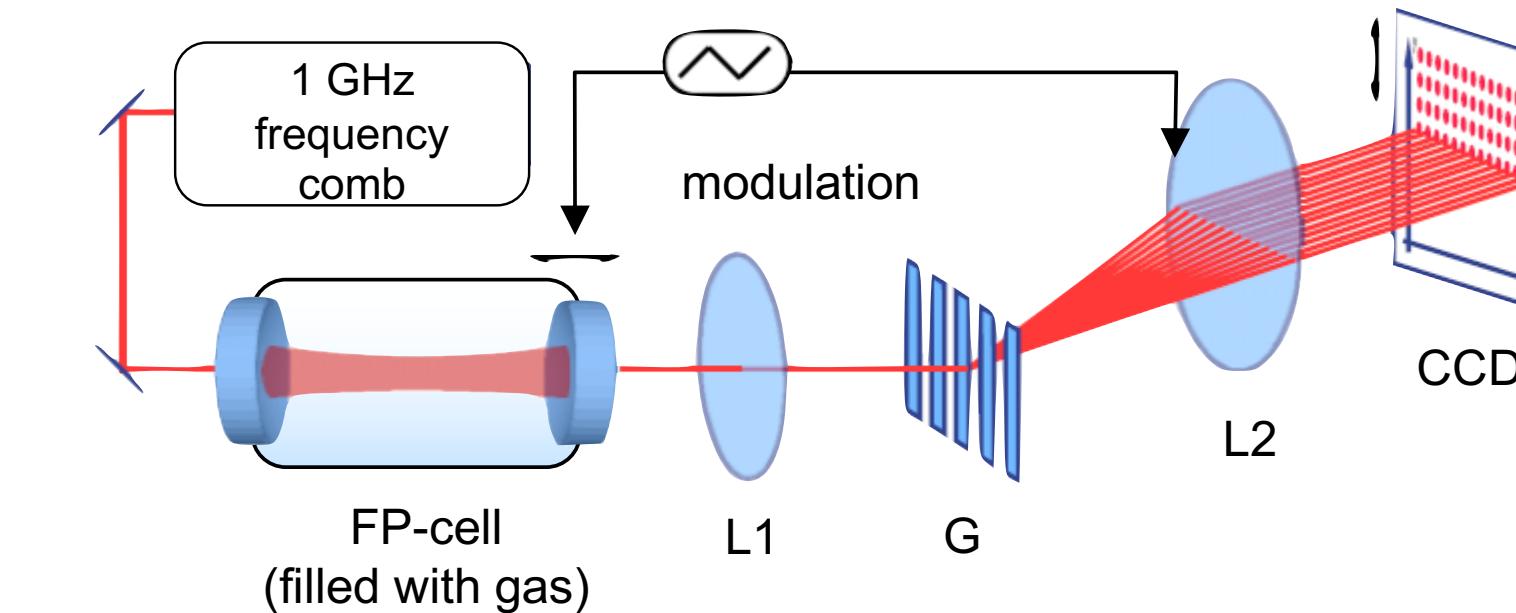
## Dispersive methods

- Virtually Imaged Phased Array (VIPA)



S. A. Diddams et al., Nature **445**, 627 (2007)

- Vernier spectroscopy

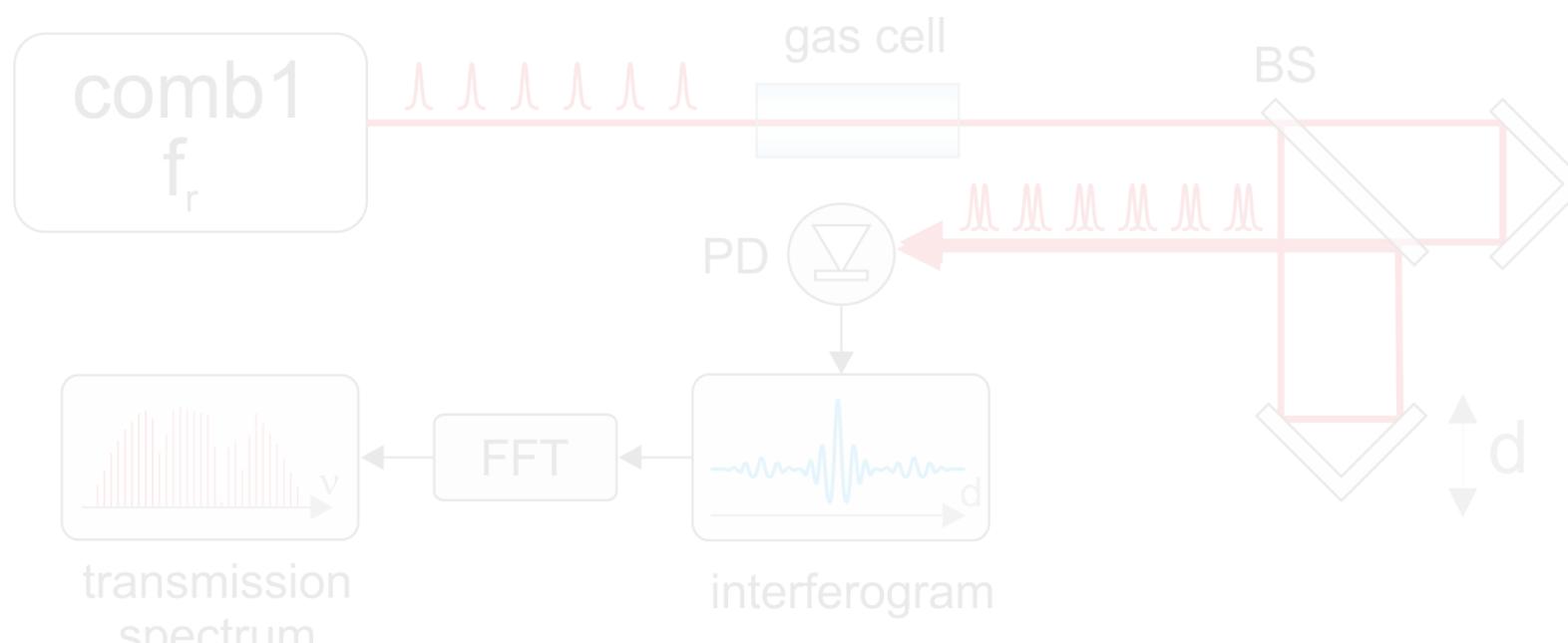


C. Gohle, et al. Phys. Rev. Lett. **99**, 263902 (2007)

# Direct - Frequency comb spectroscopy

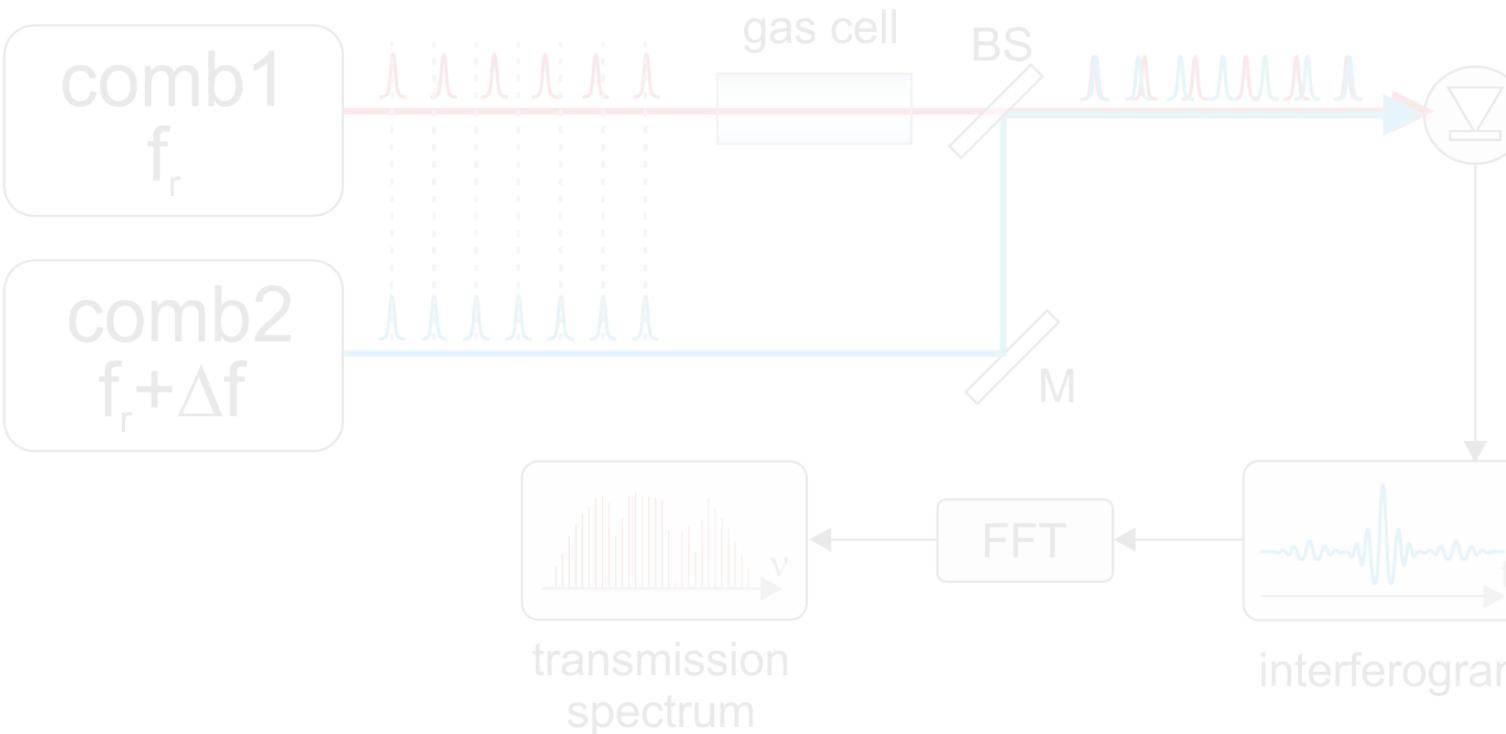
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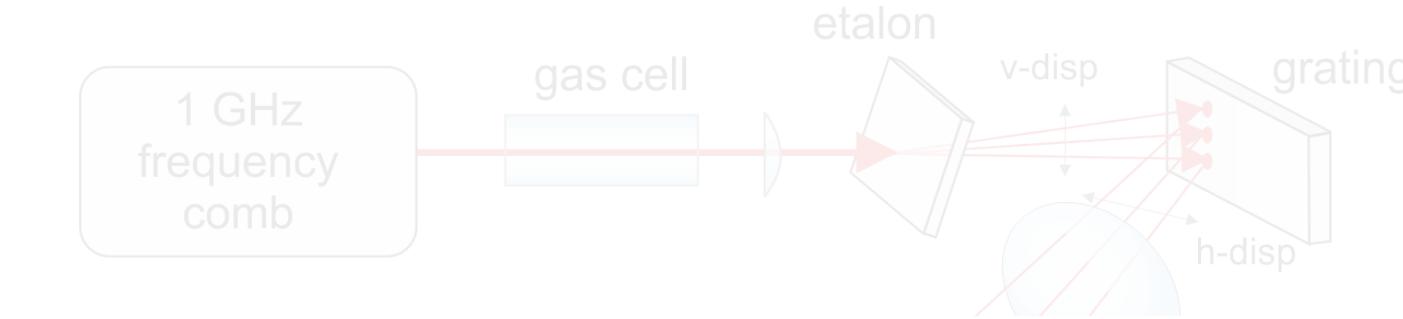
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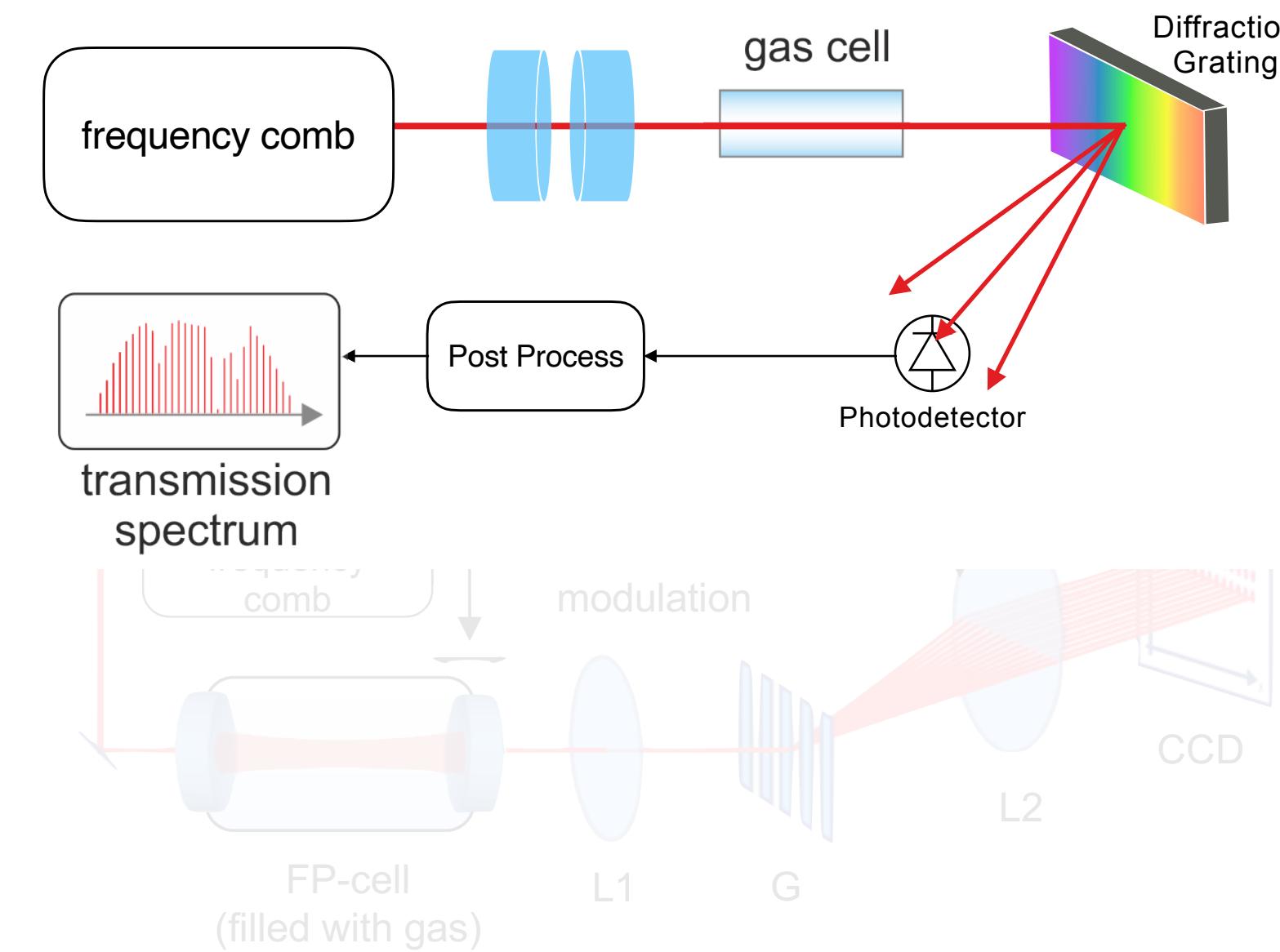
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## Dispersive methods

- Virtually Imaged Phased Array (VIPA)



- SMART spectroscopy



C. Gohle, et al. Phys. Rev. Lett. 99, 263902 (2007)

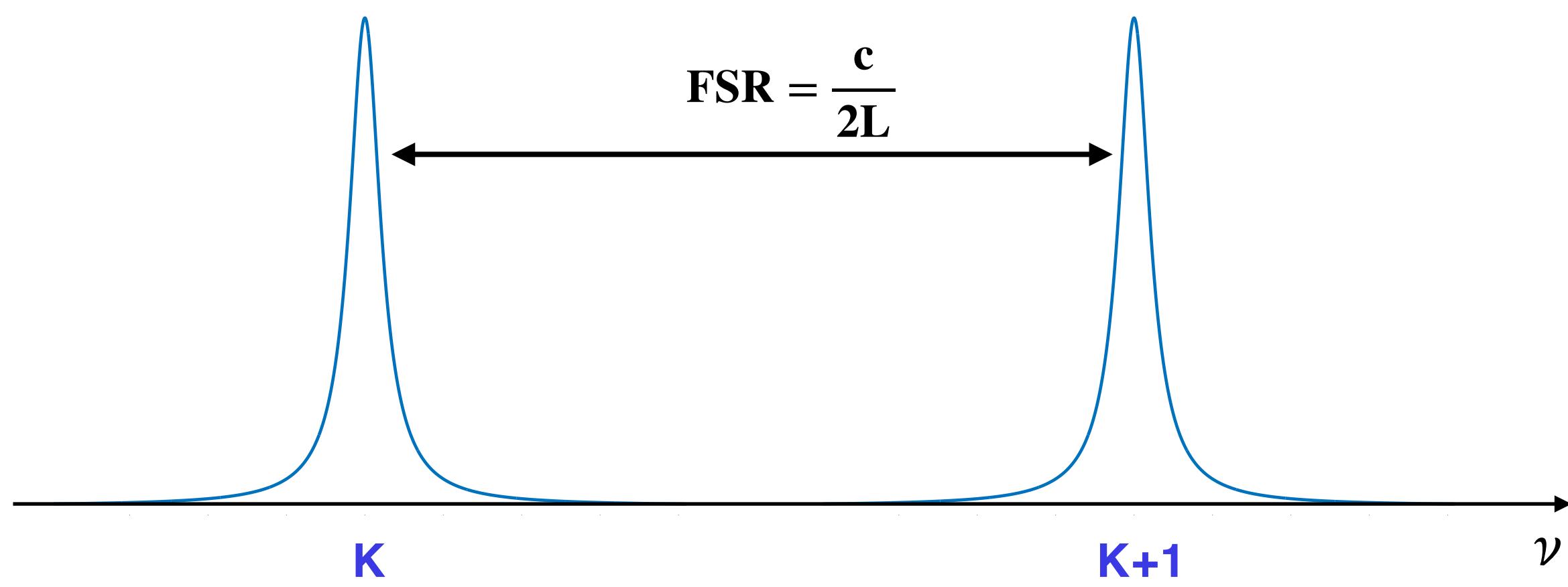
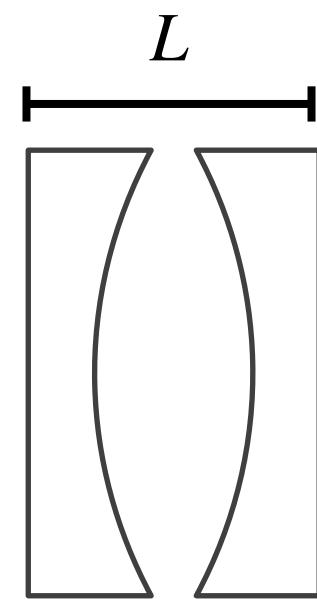
## SMART principle

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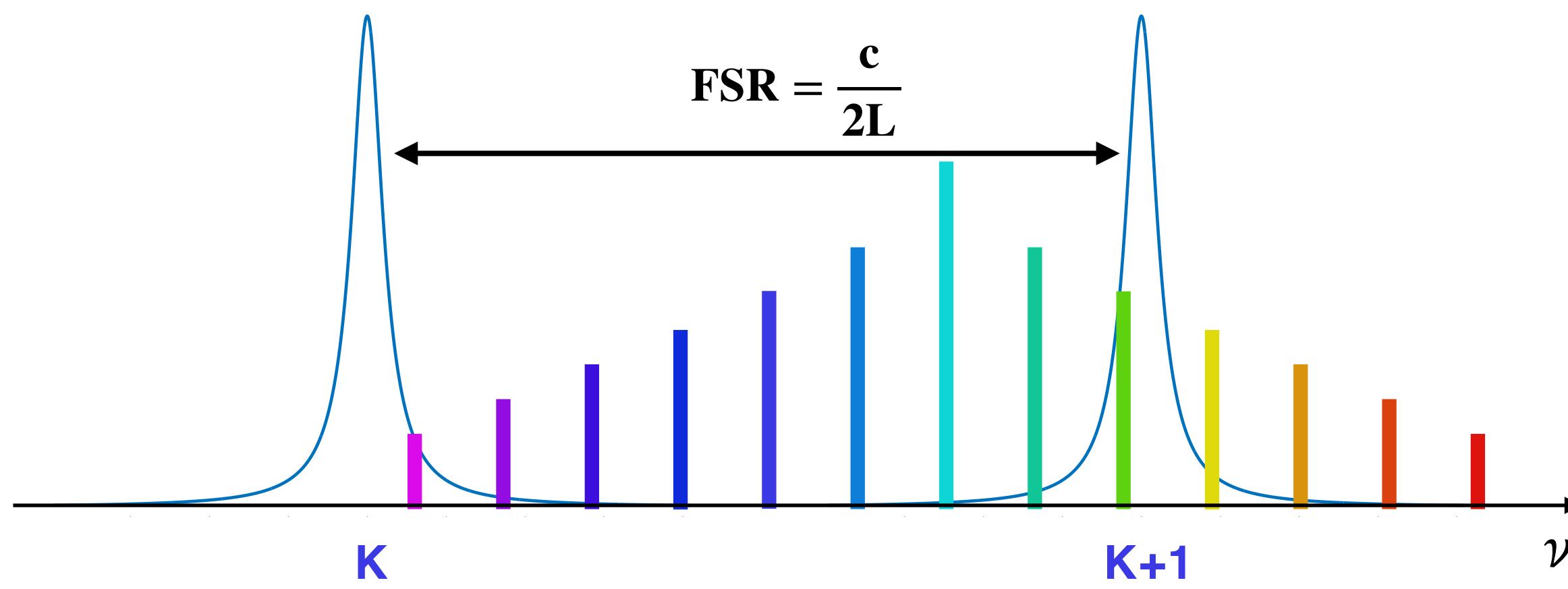
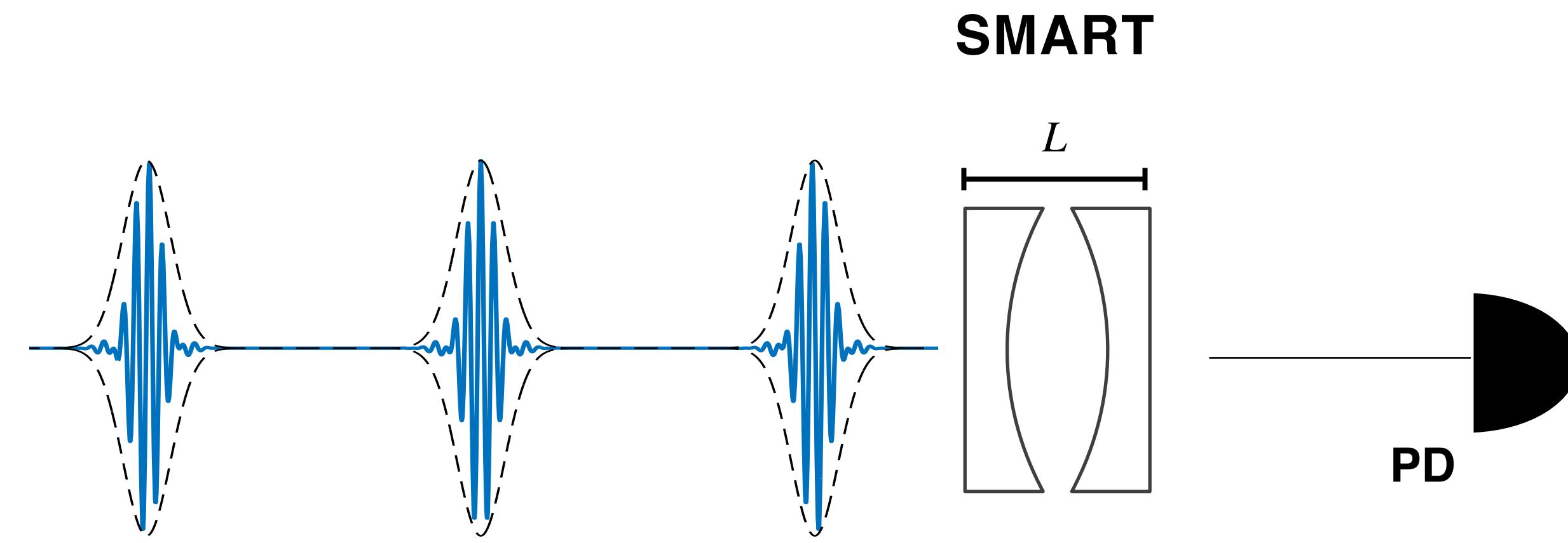
**SMART**

## SMART principle

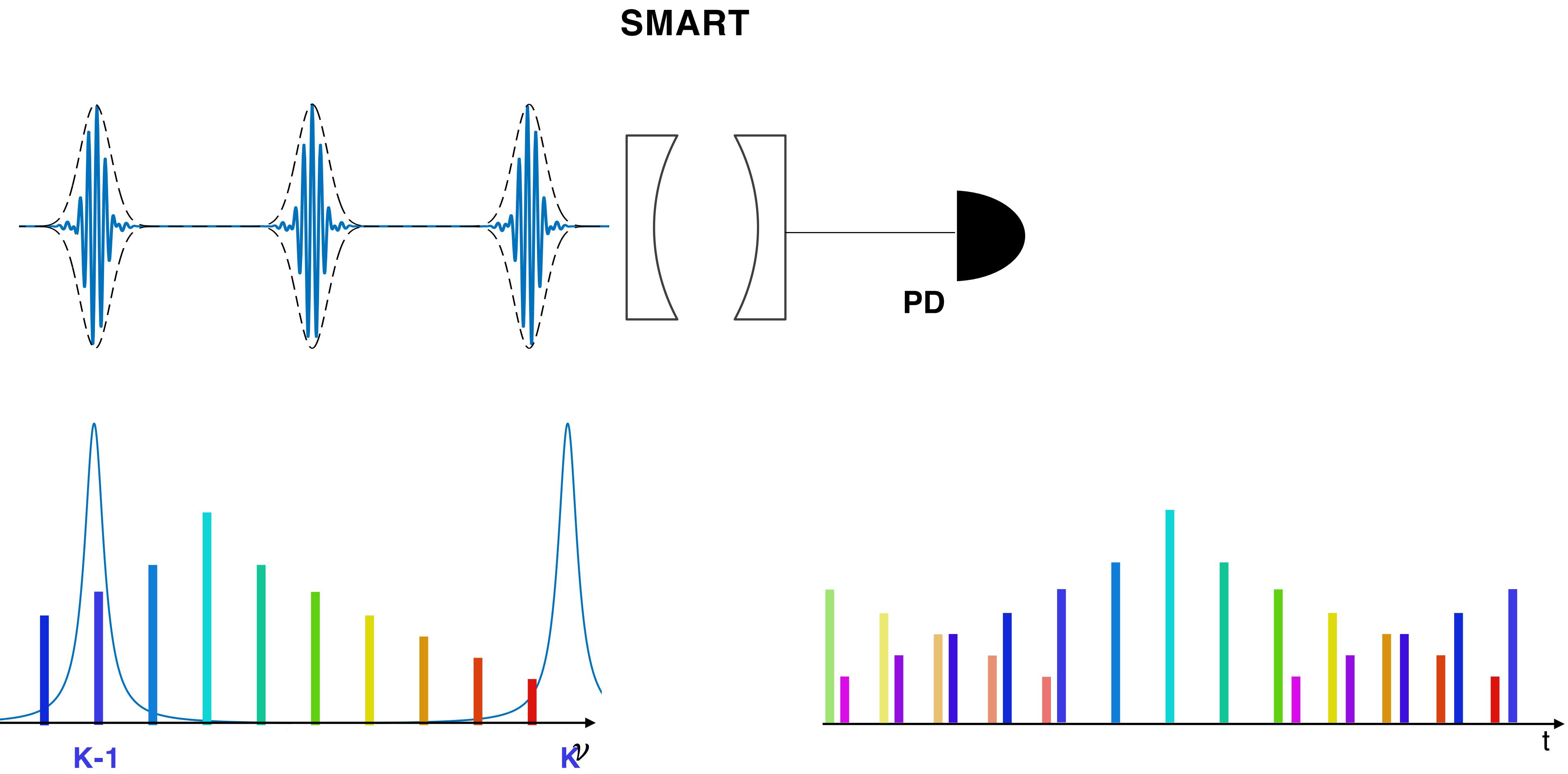
**SMART**



## SMART principle

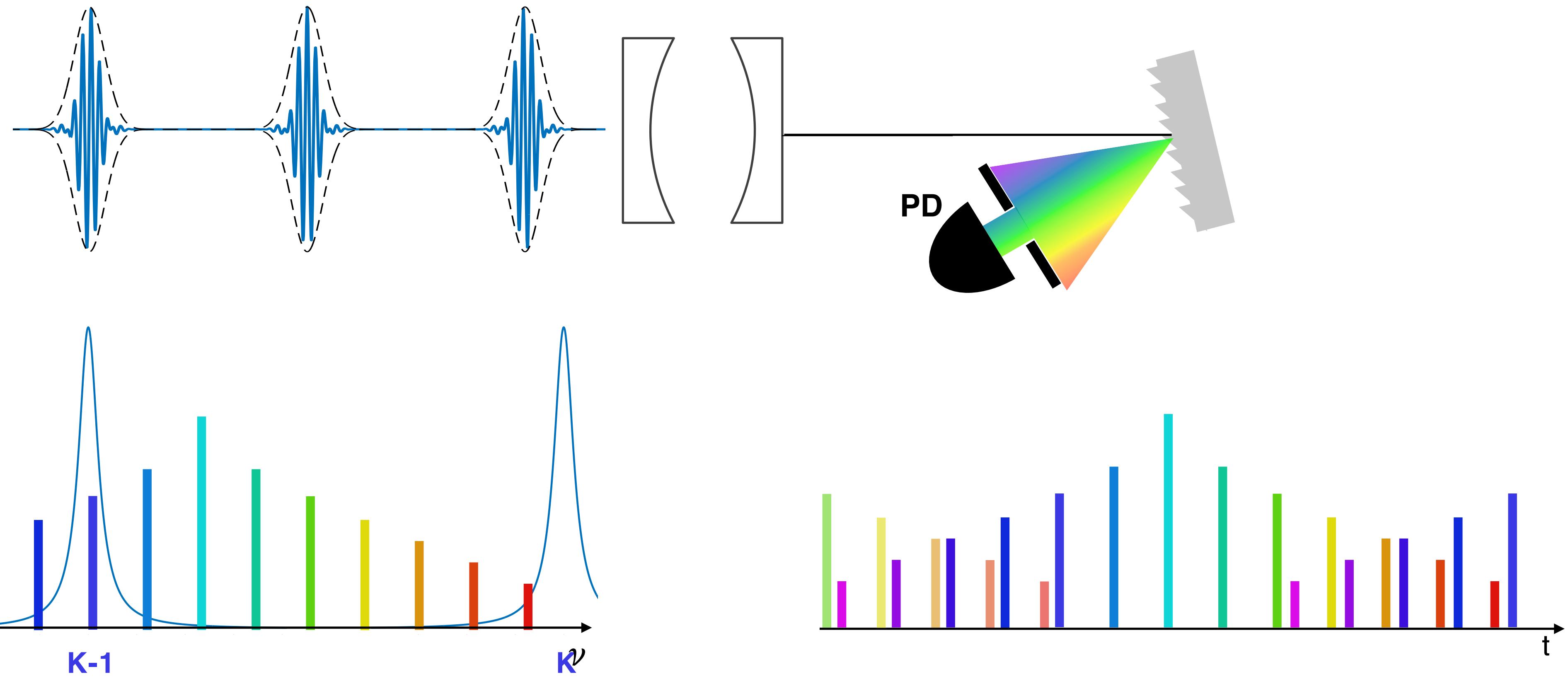


## SMART principle



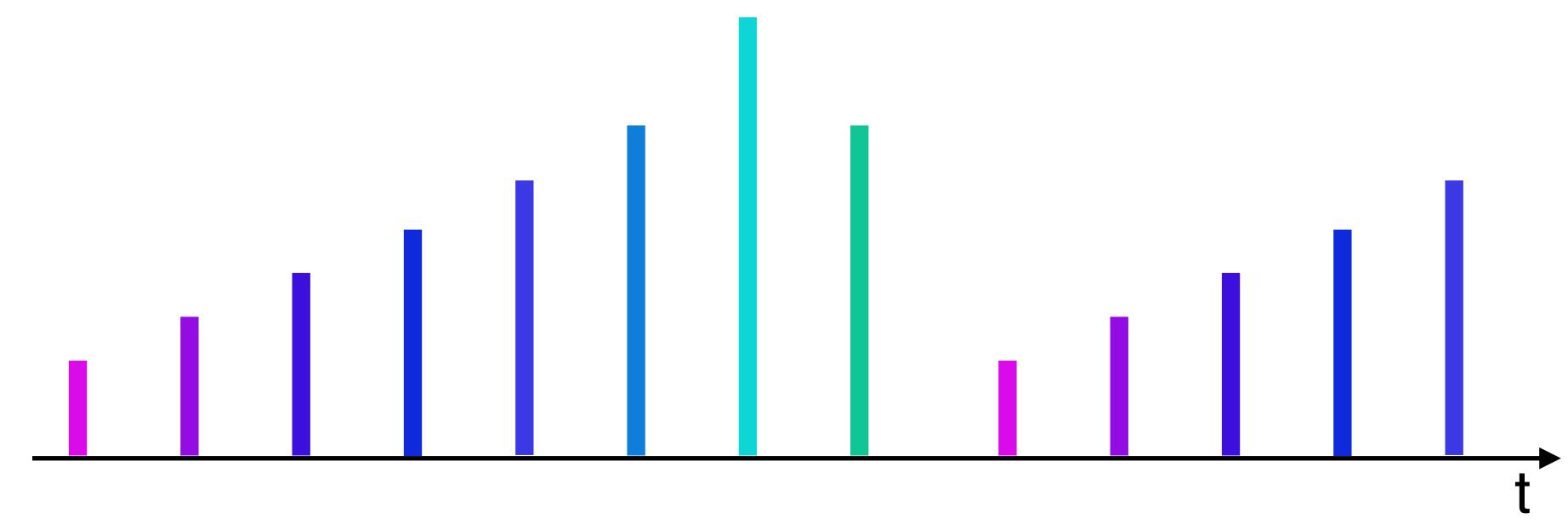
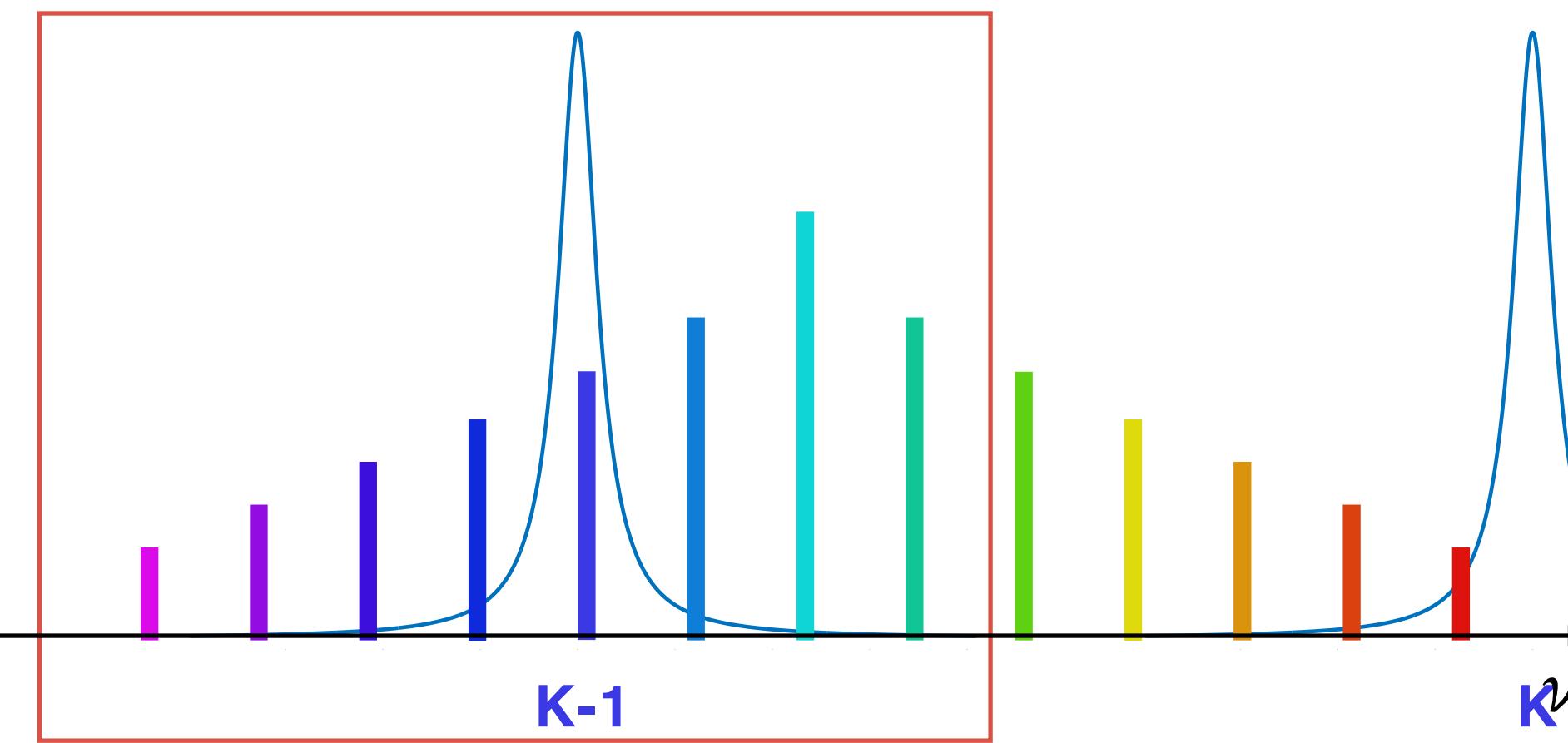
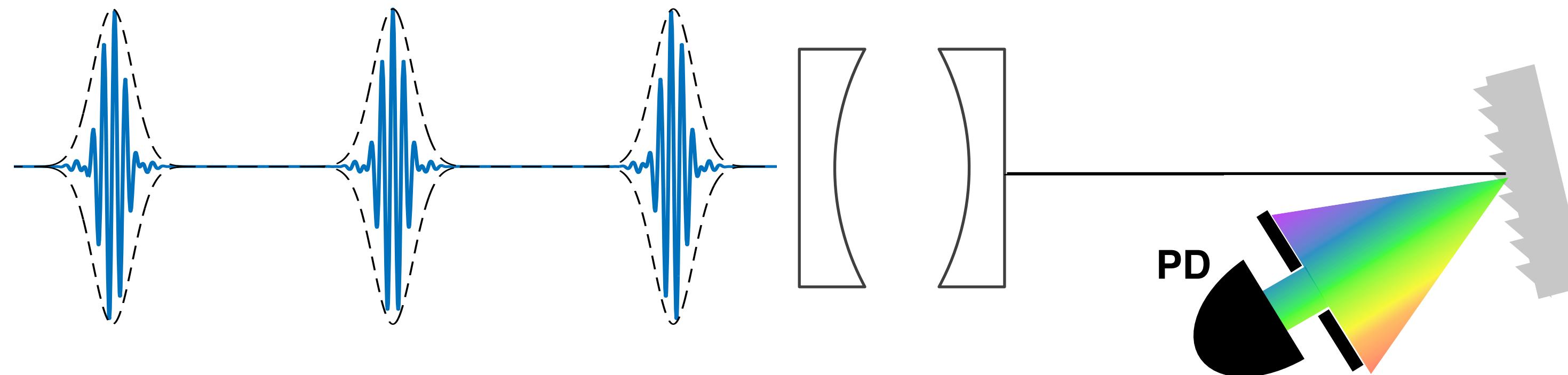
## SMART principle

SMART



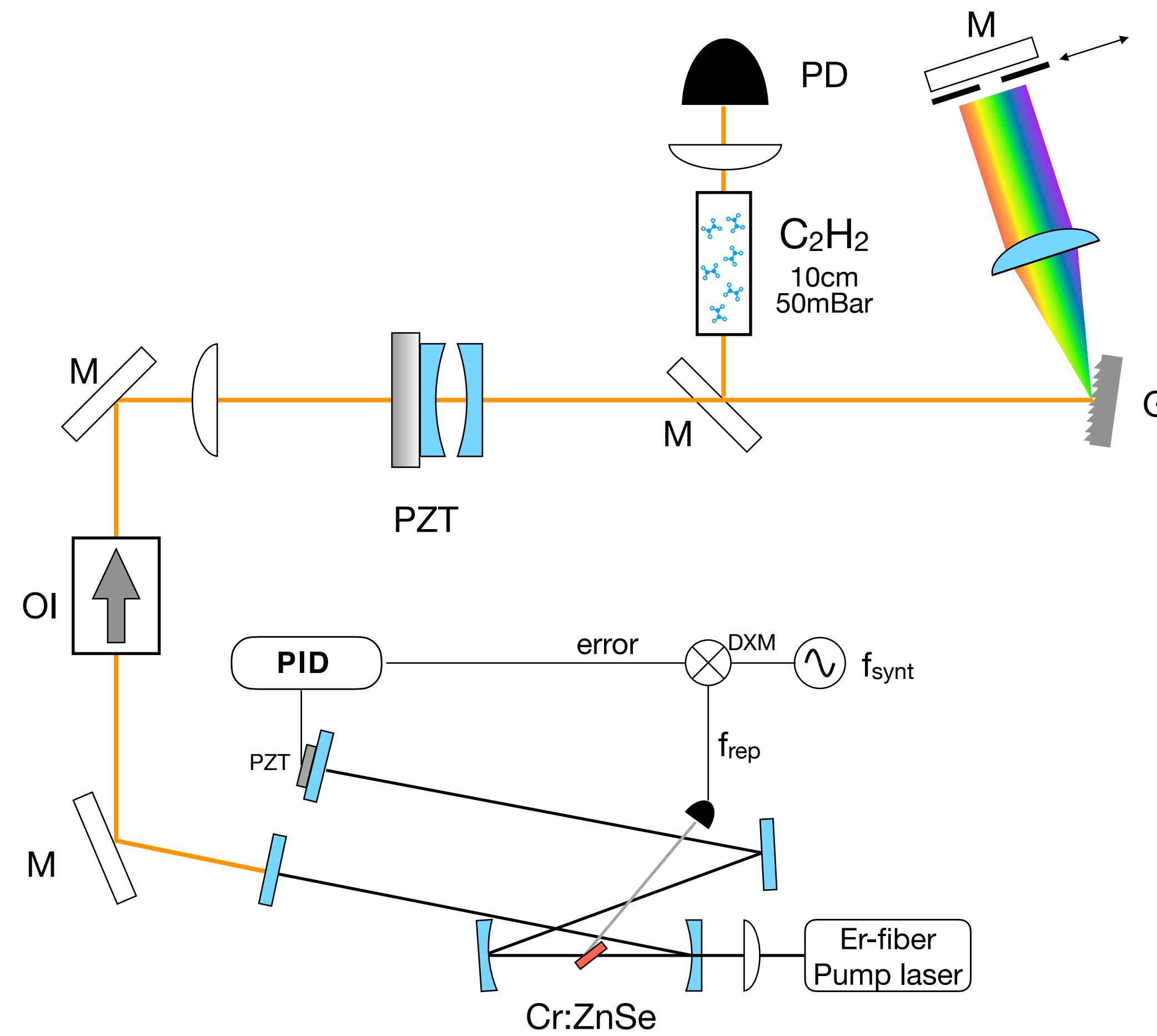
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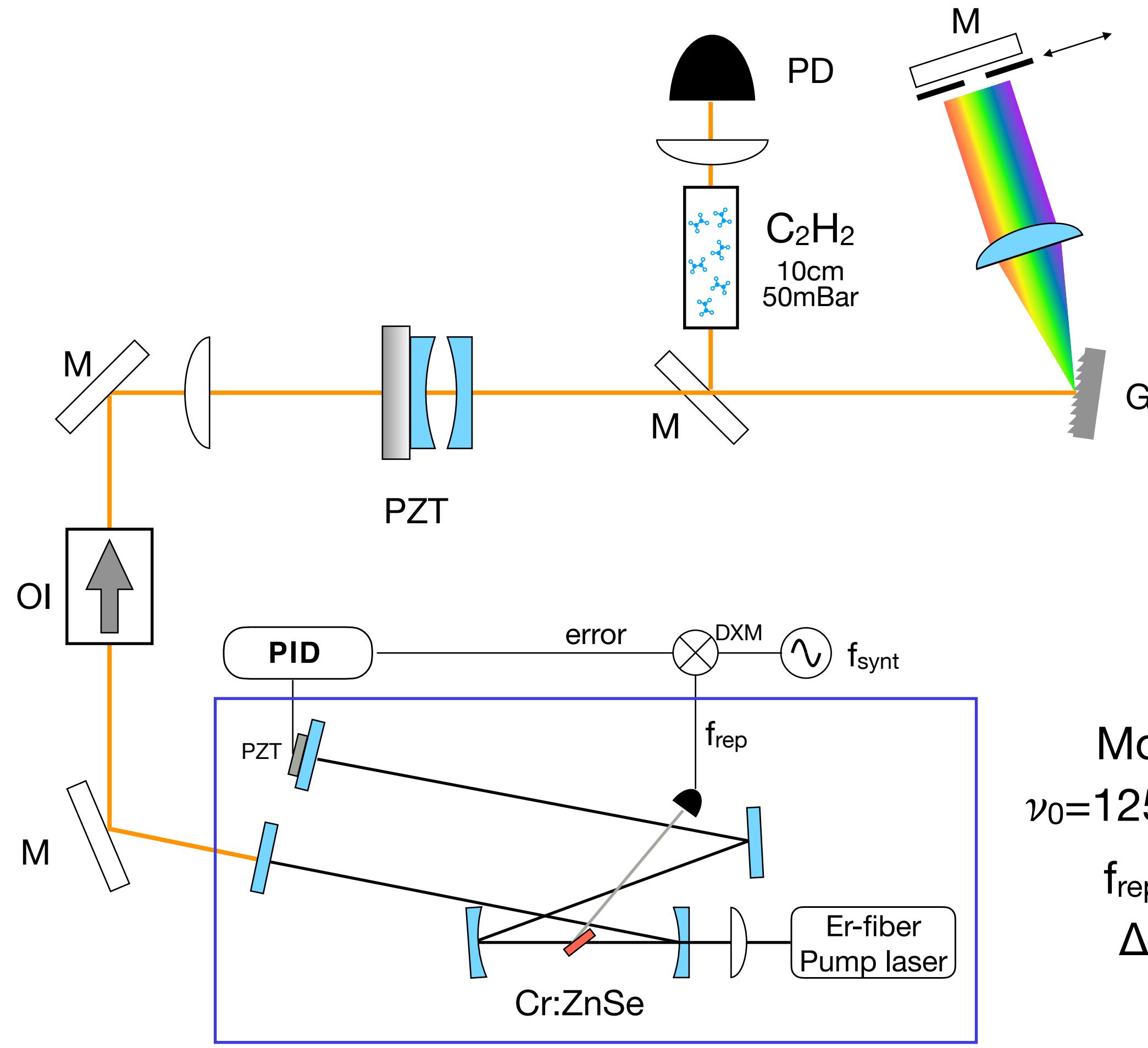


## Experimental setup

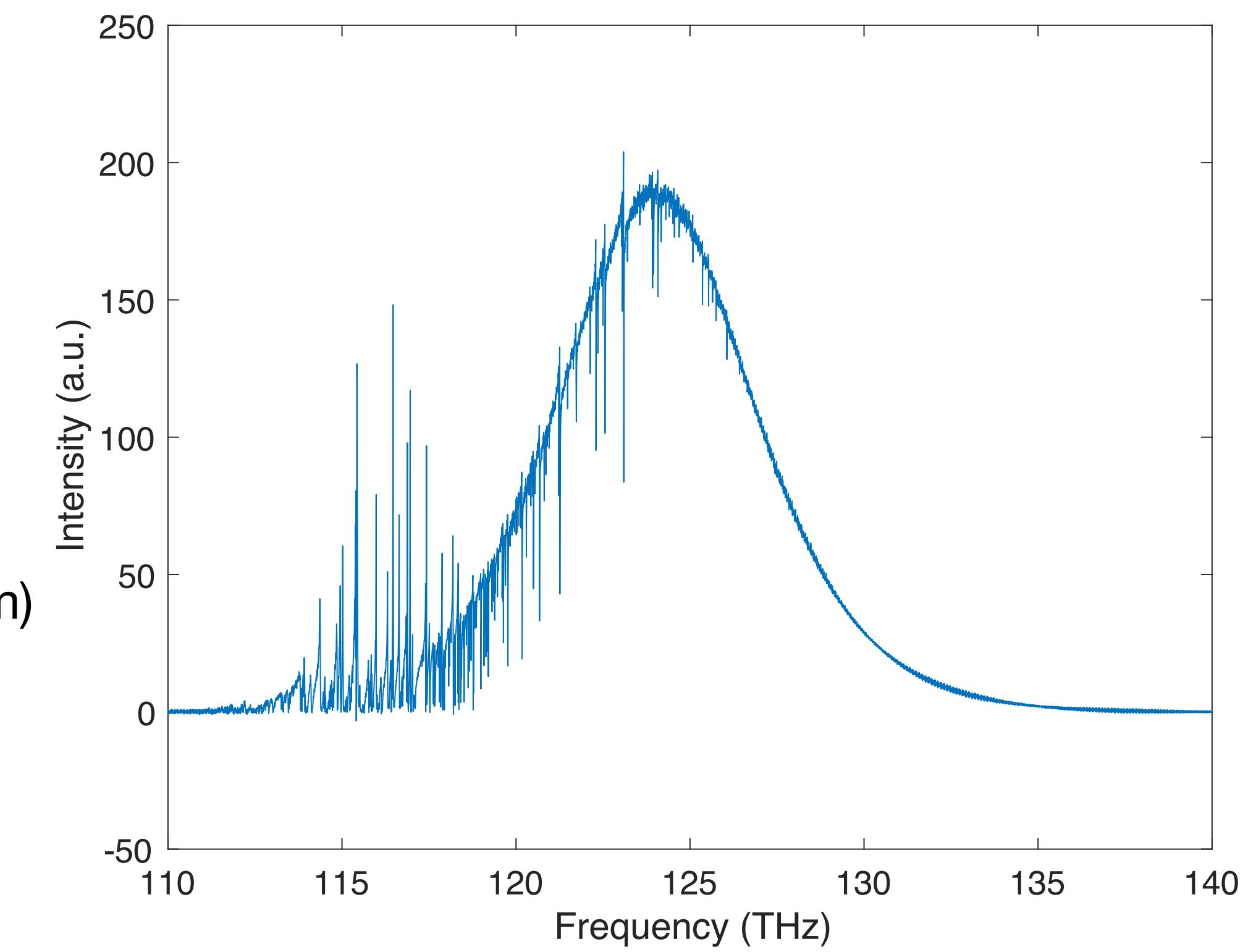
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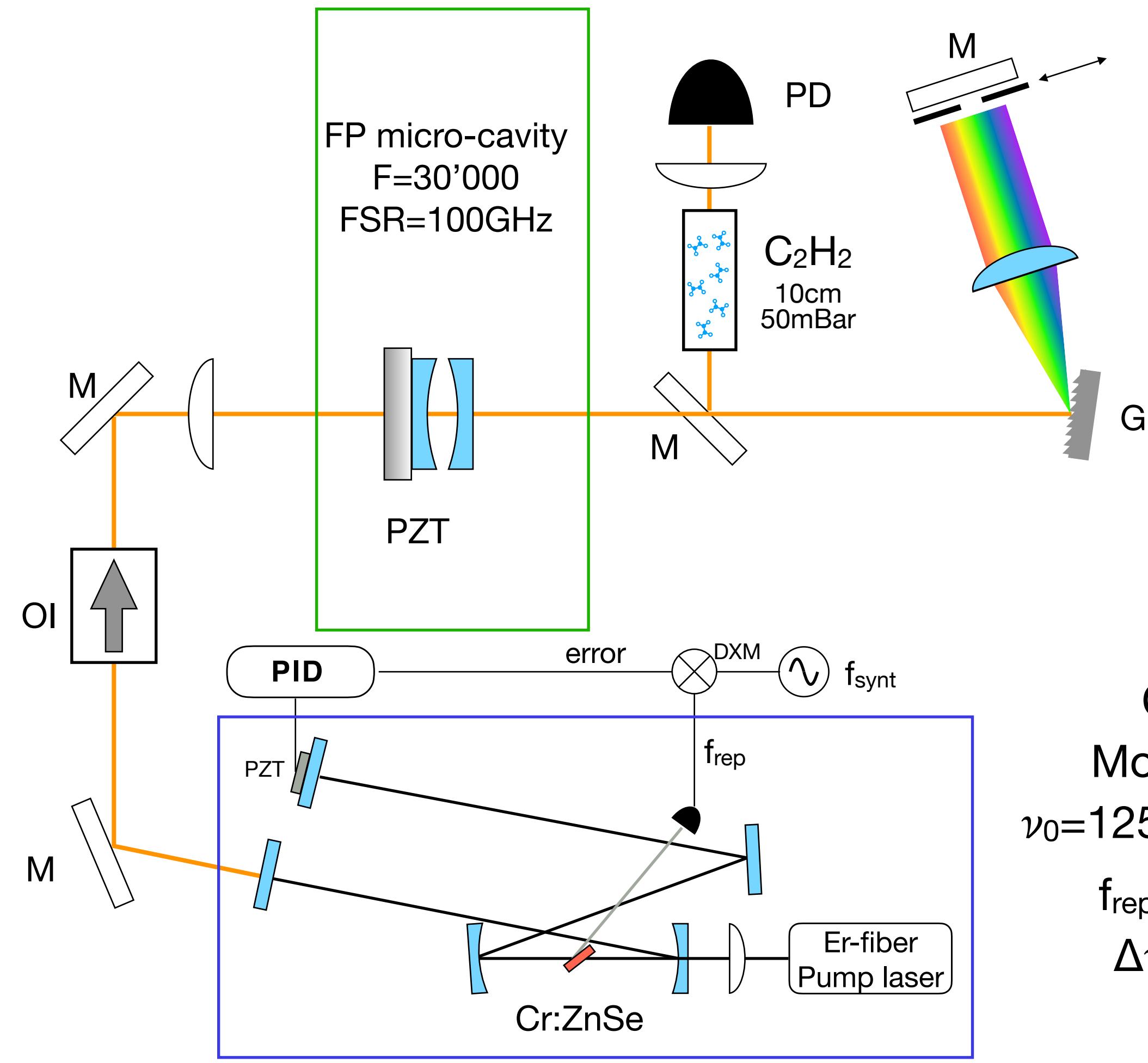
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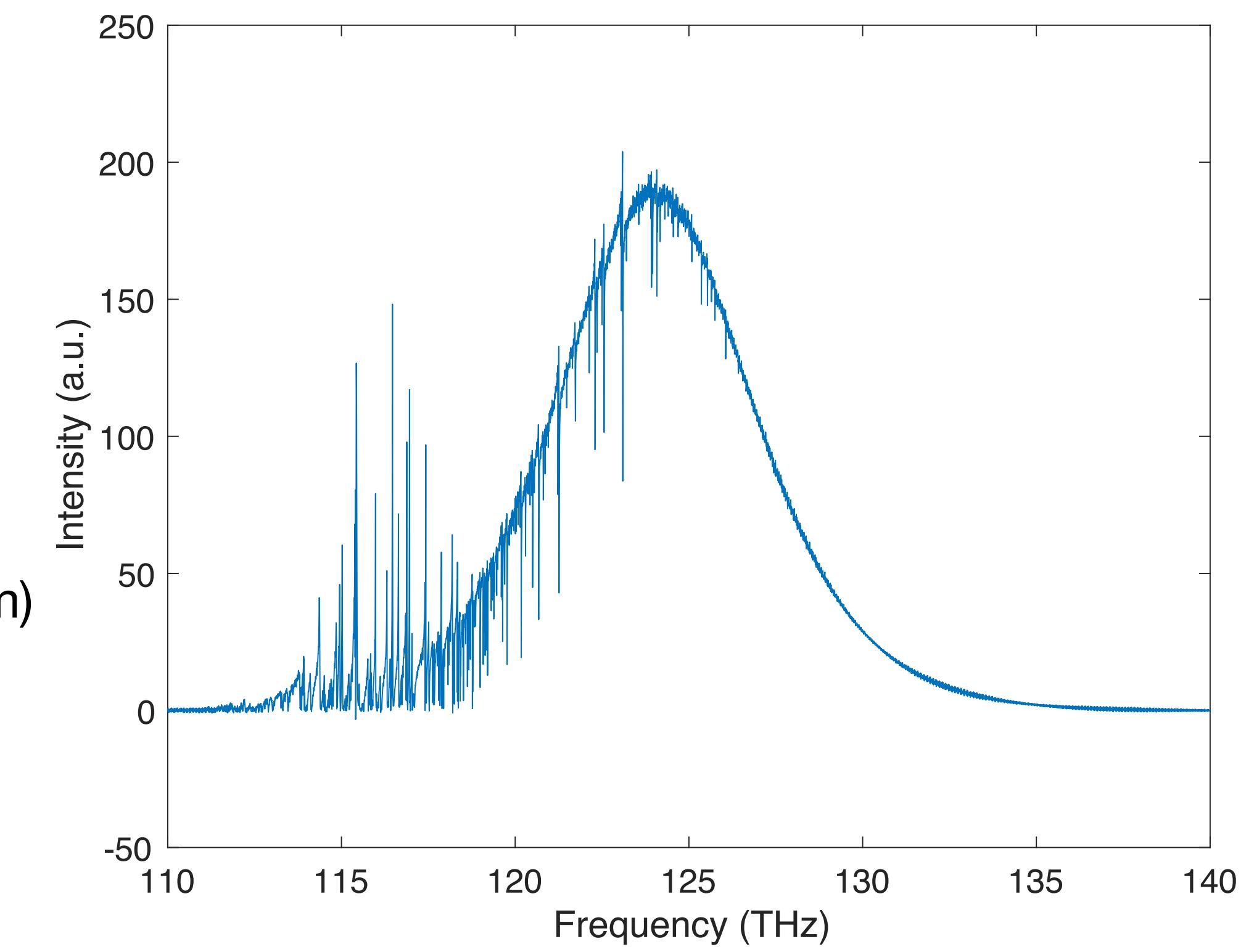
**Cr:ZnSe**  
Mode-locked  
 $\nu_0=125 \text{ THz (}2.4 \mu\text{m)}$   
 $f_{\text{rep}}=220 \text{ MHz}$   
 $\Delta\nu=12 \text{ THz}$   
150mW



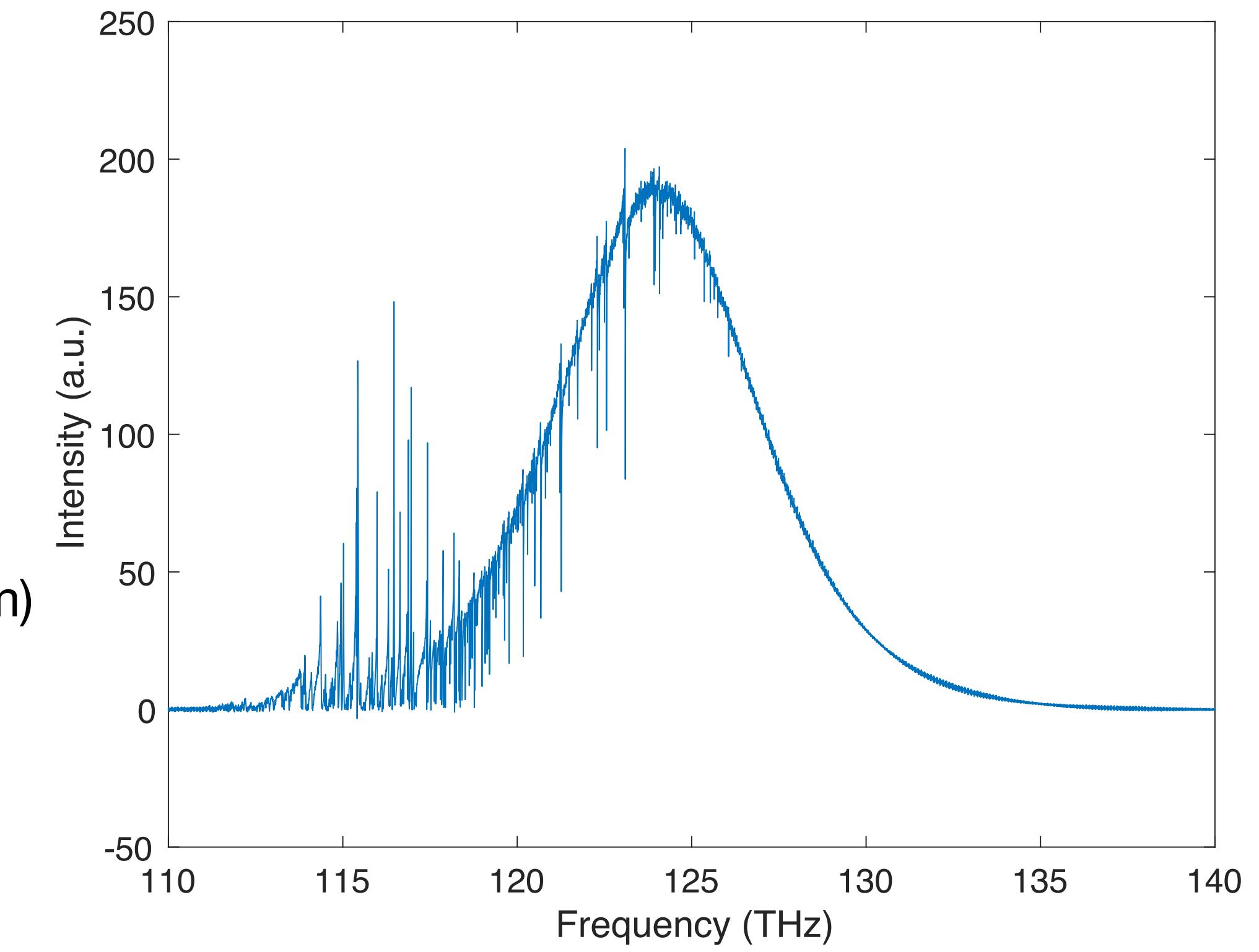
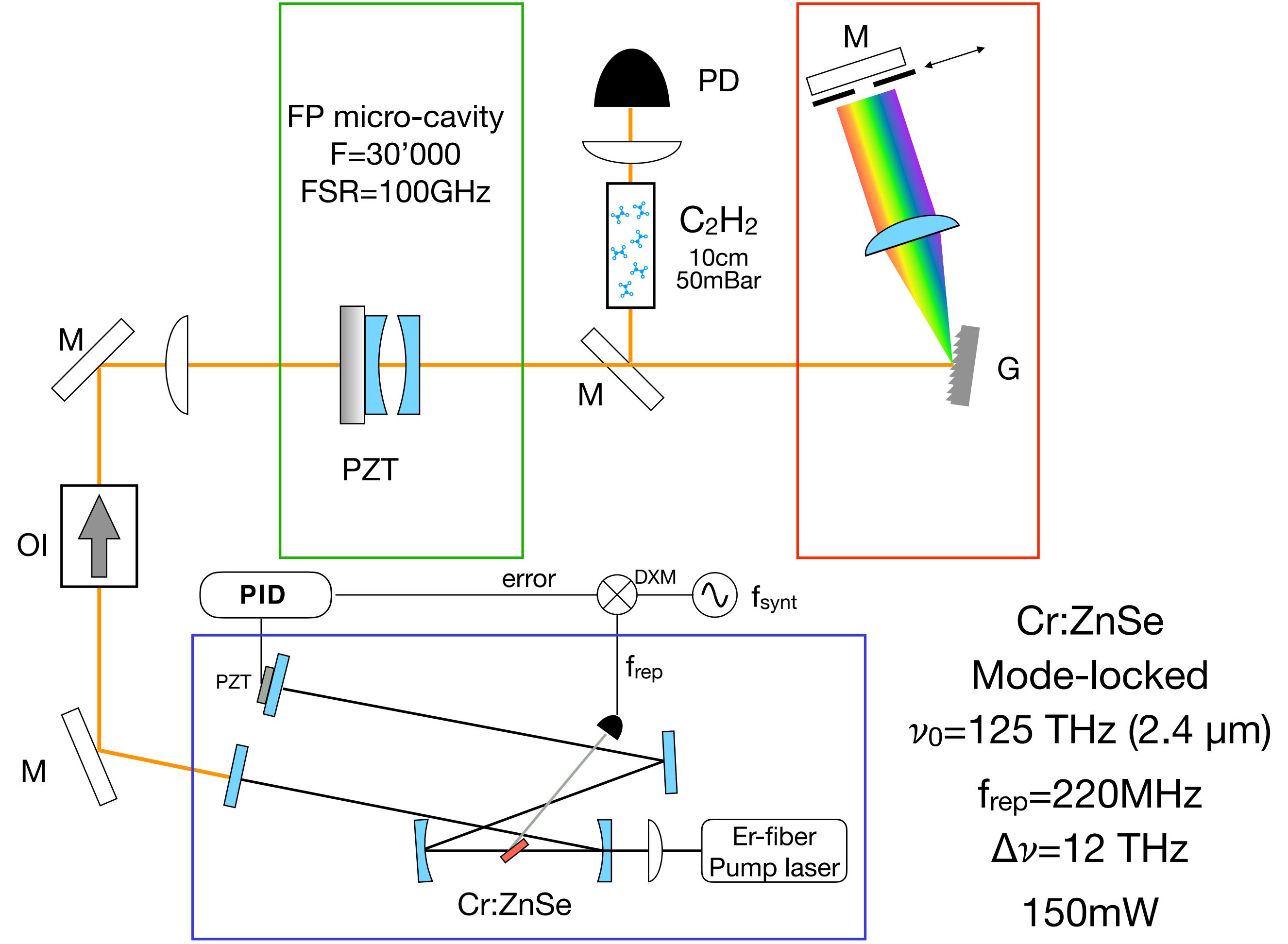
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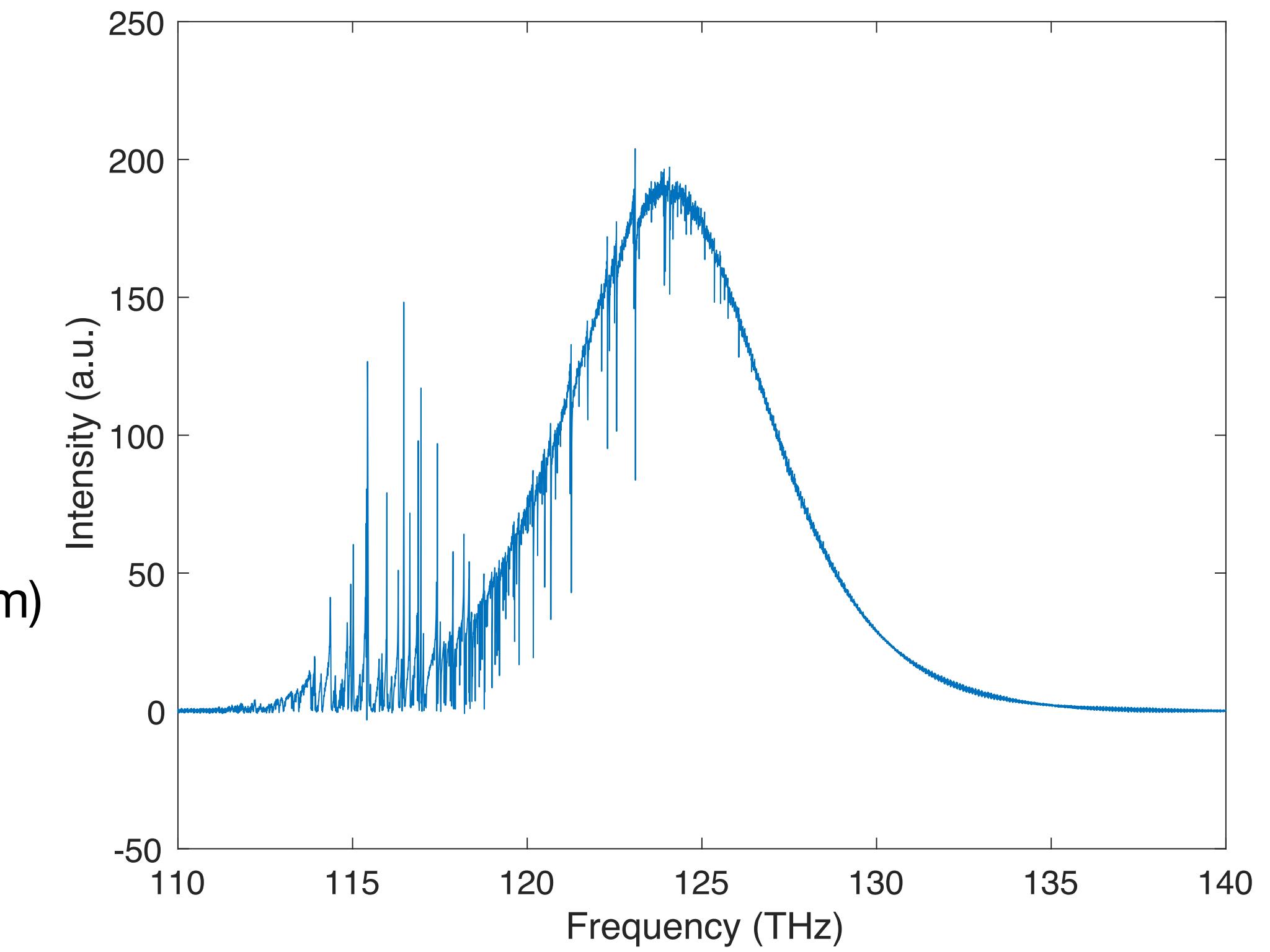
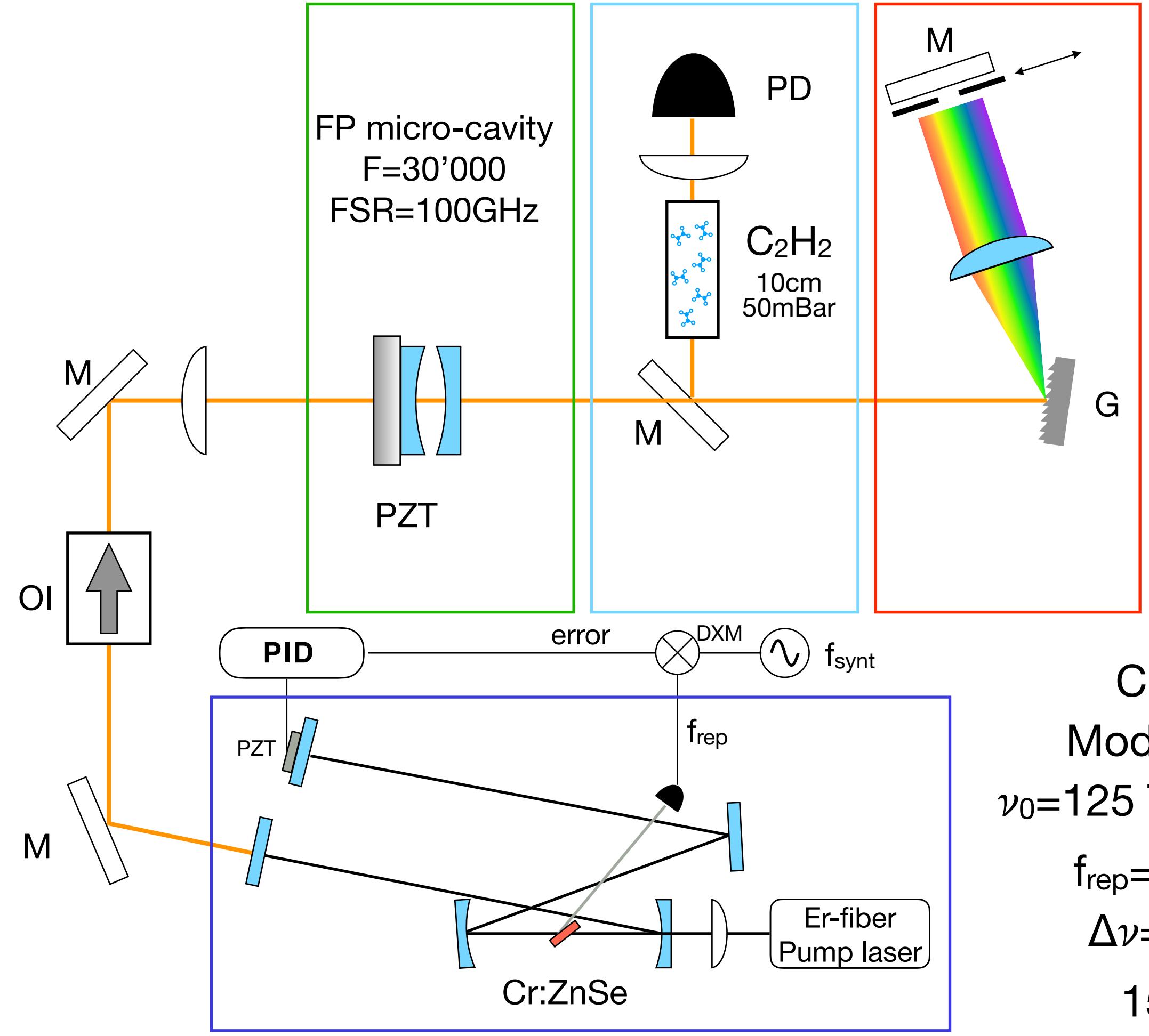
Cr:ZnSe  
Mode-locked  
 $\nu_0 = 125 \text{ THz} (2.4 \mu\text{m})$   
 $f_{\text{rep}} = 220 \text{ MHz}$   
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## Experimental setup

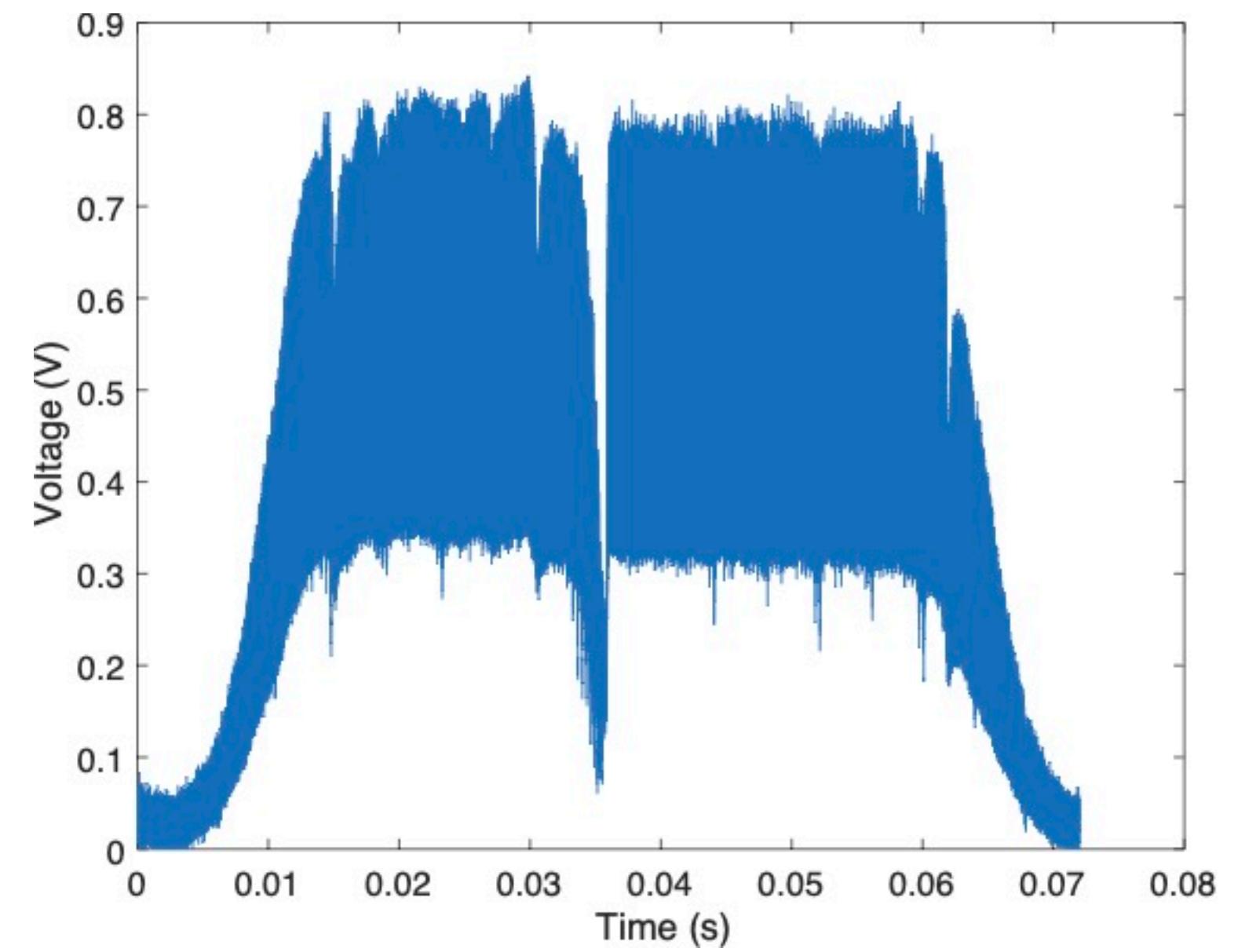


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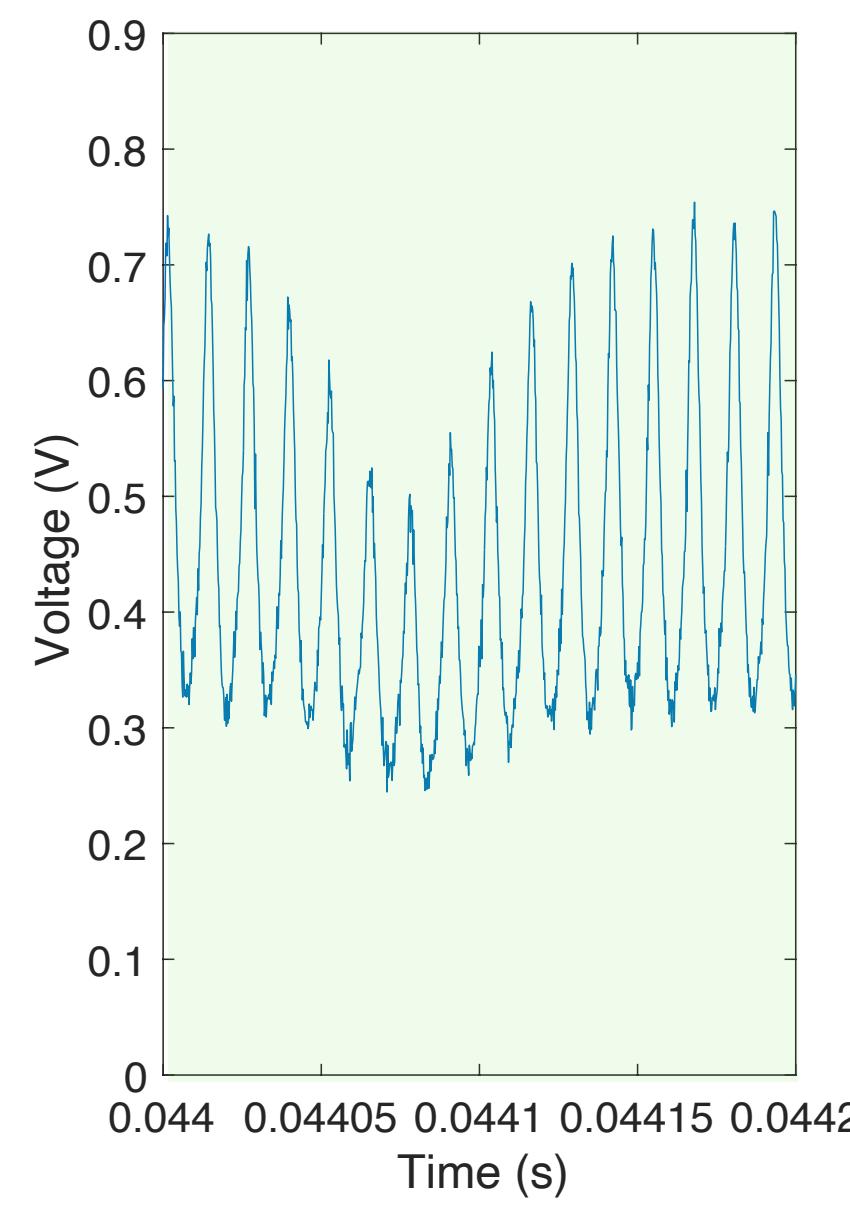
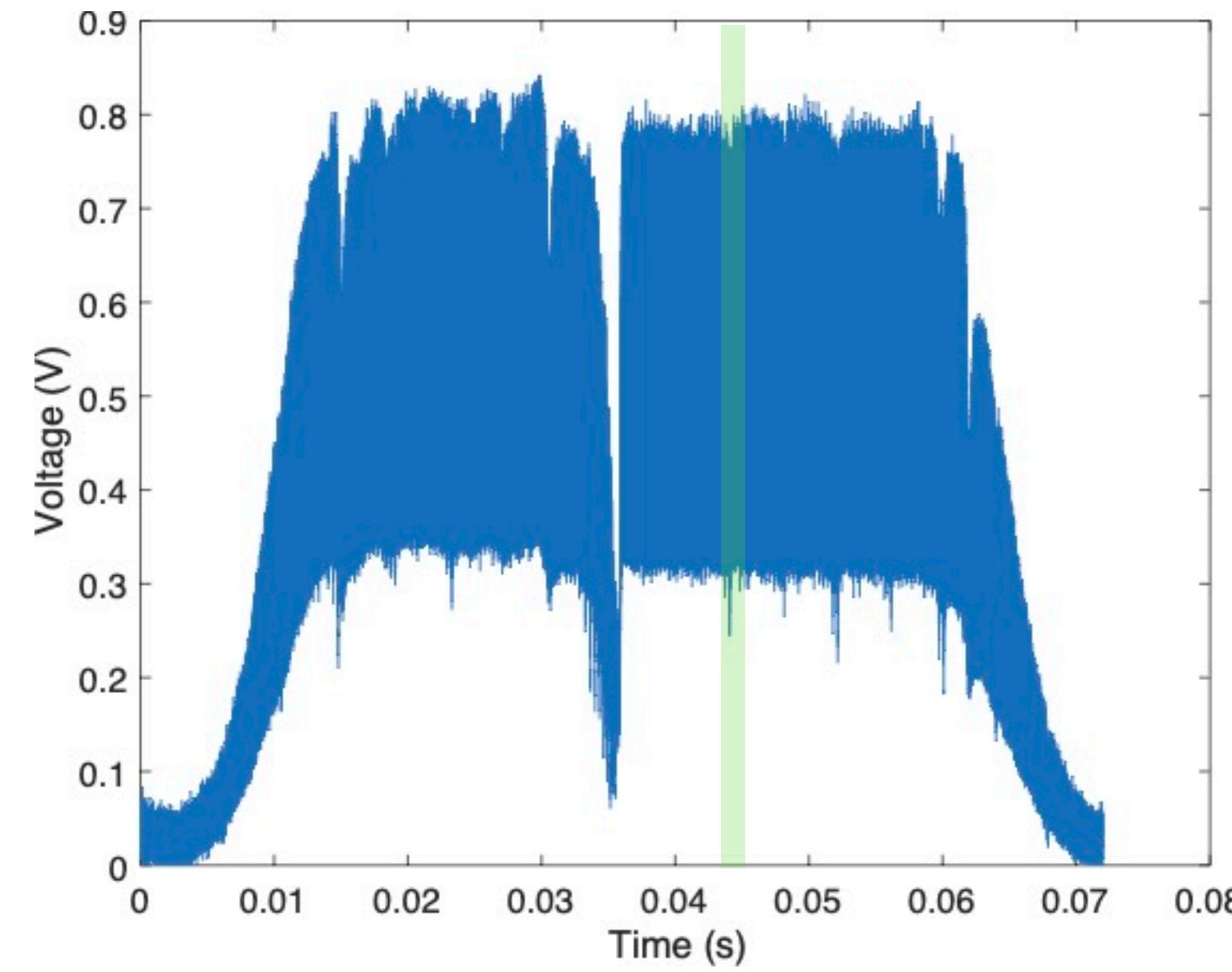


## Experimental results

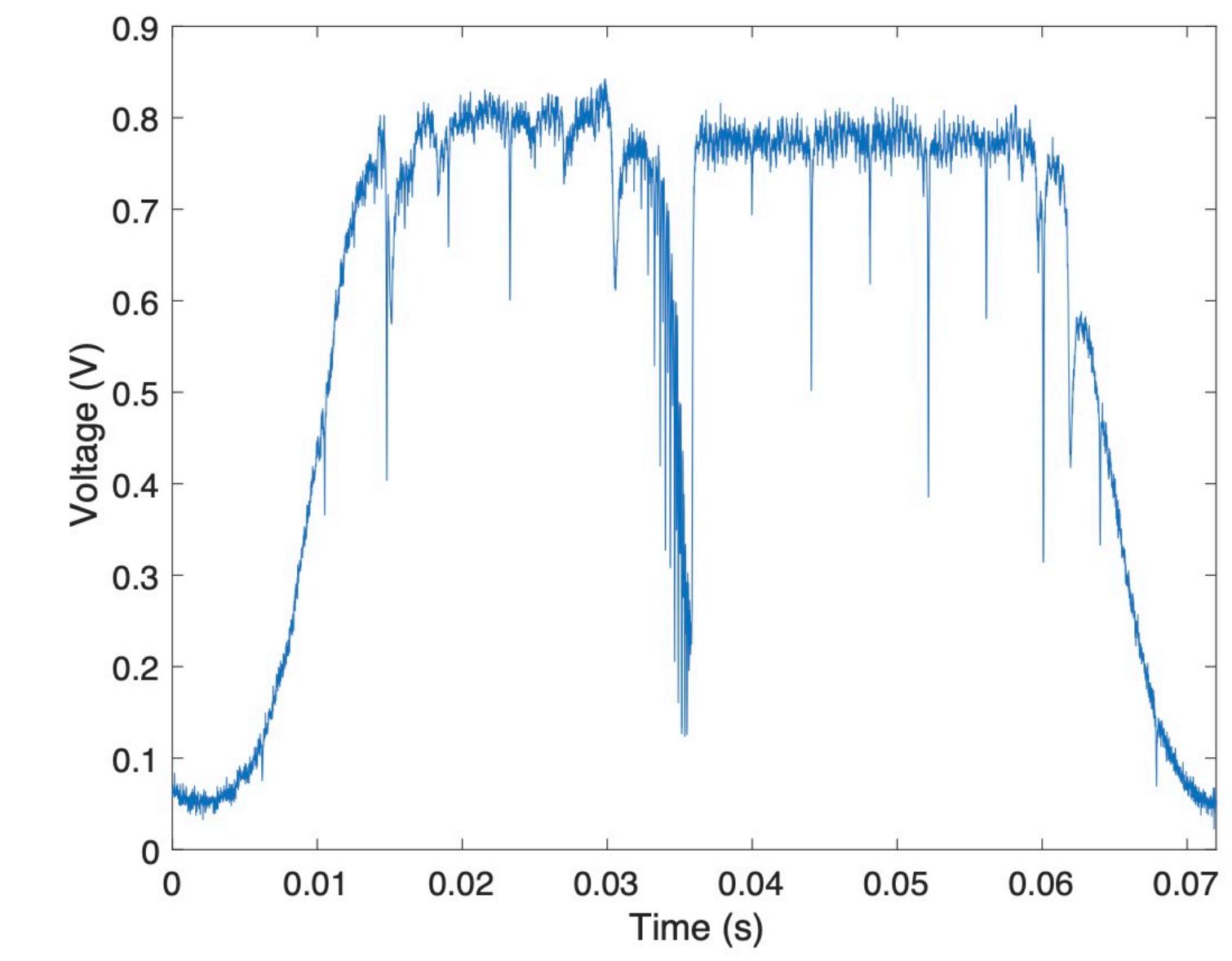
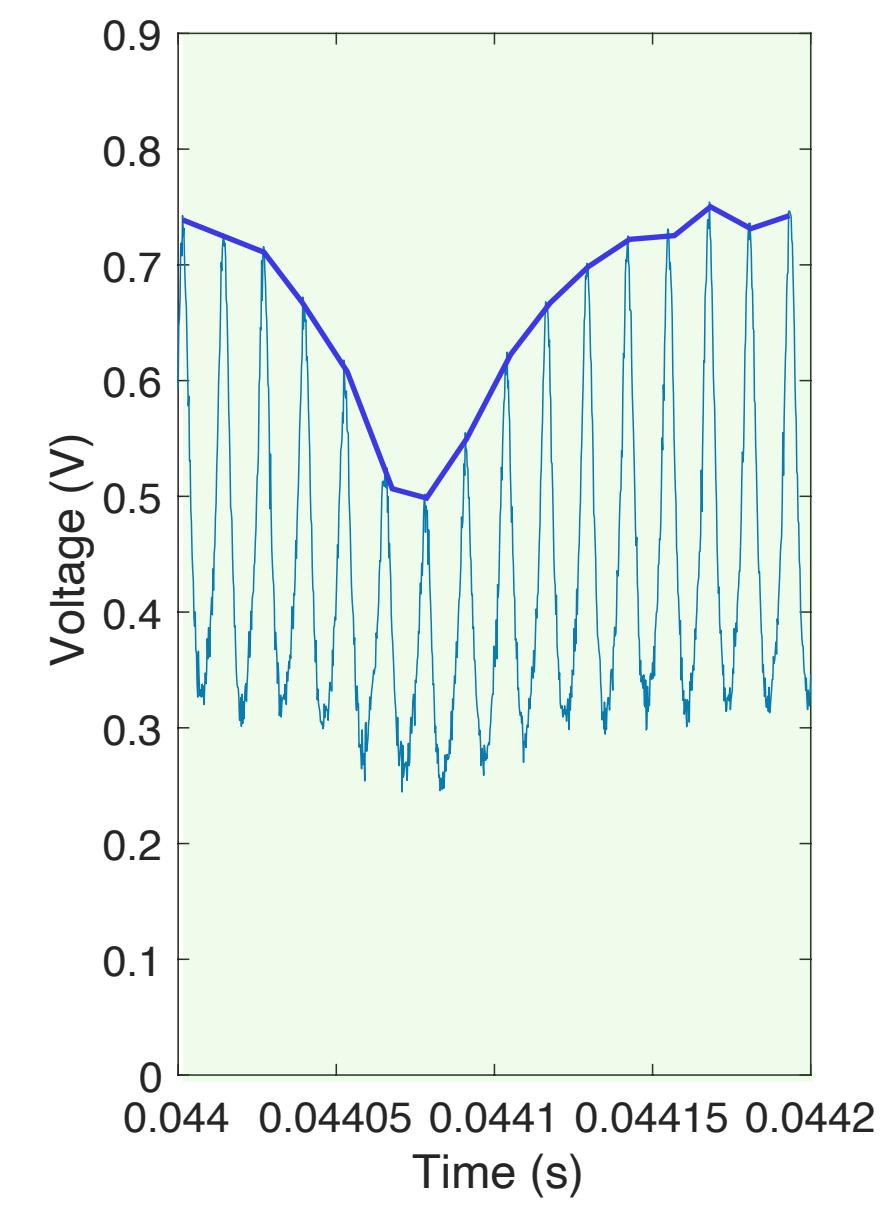
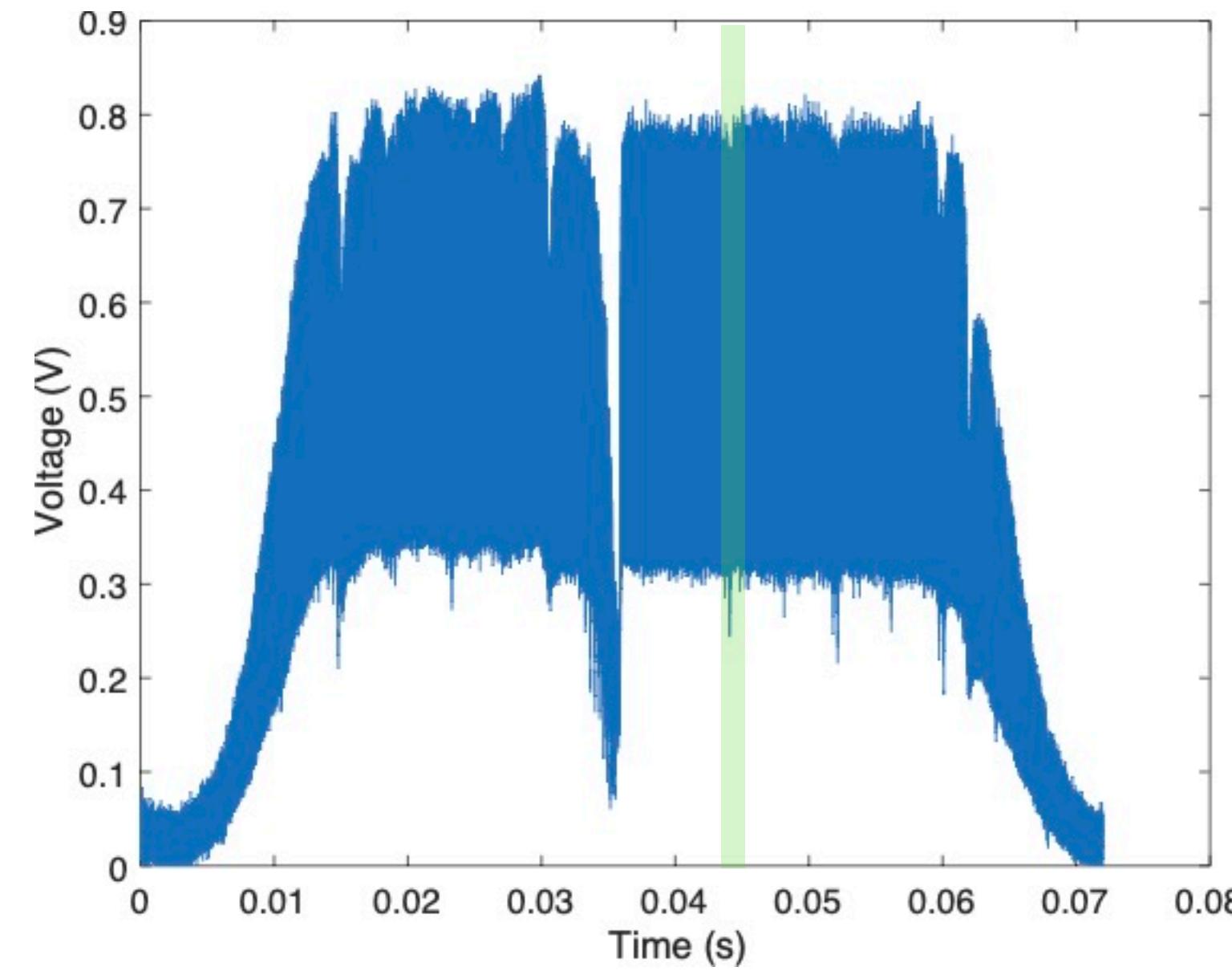
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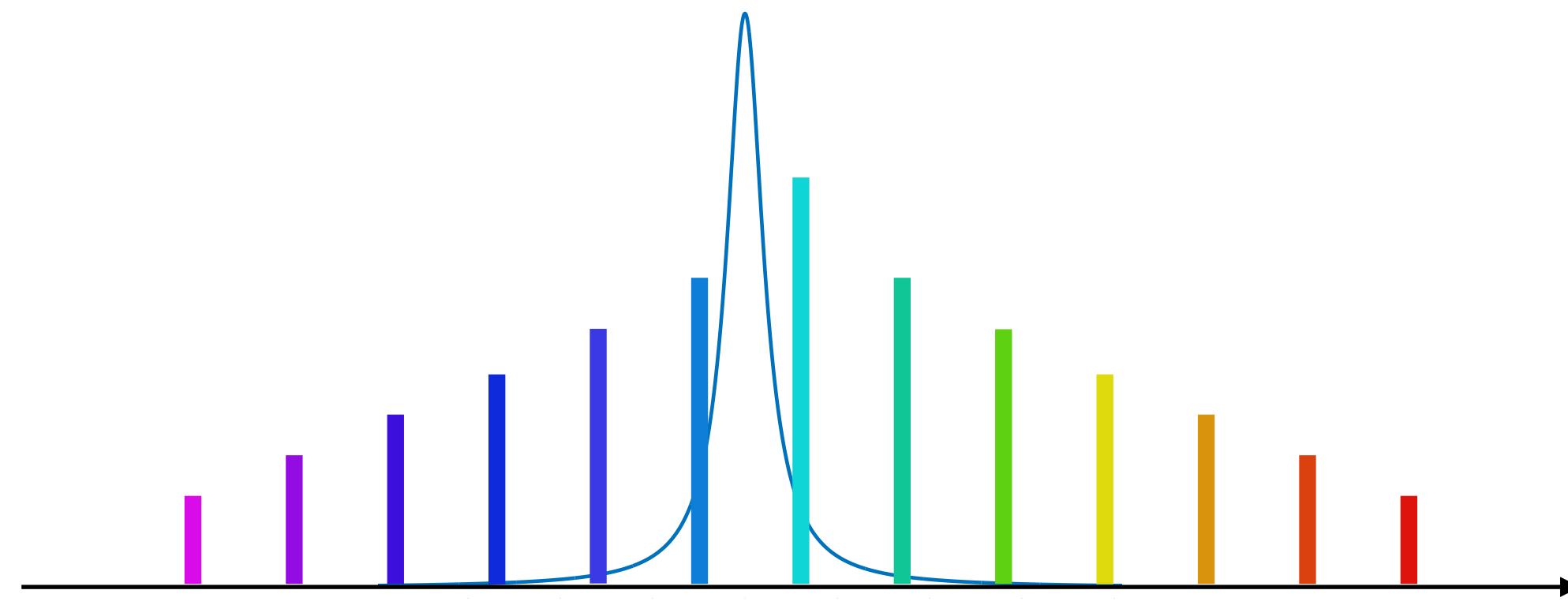
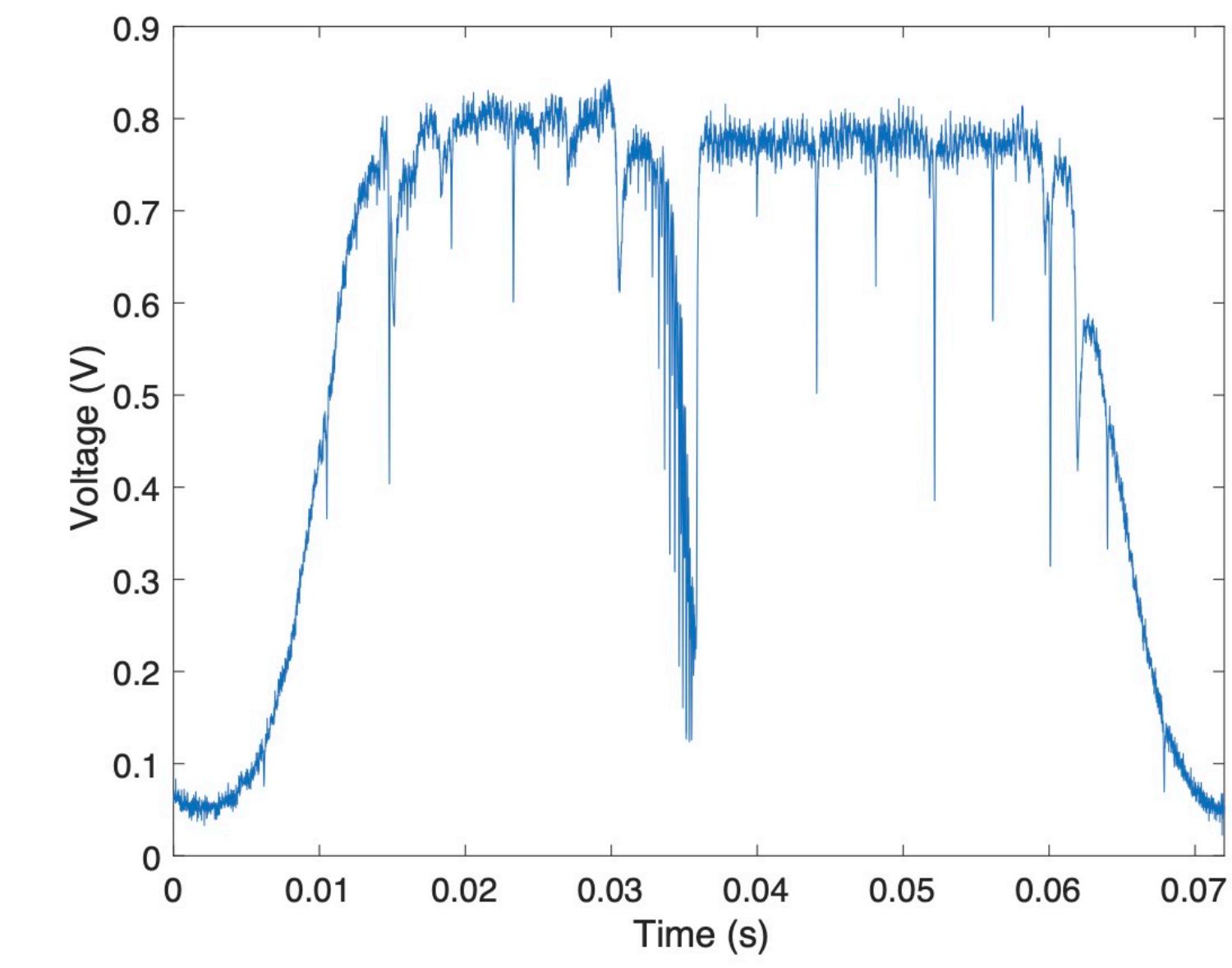
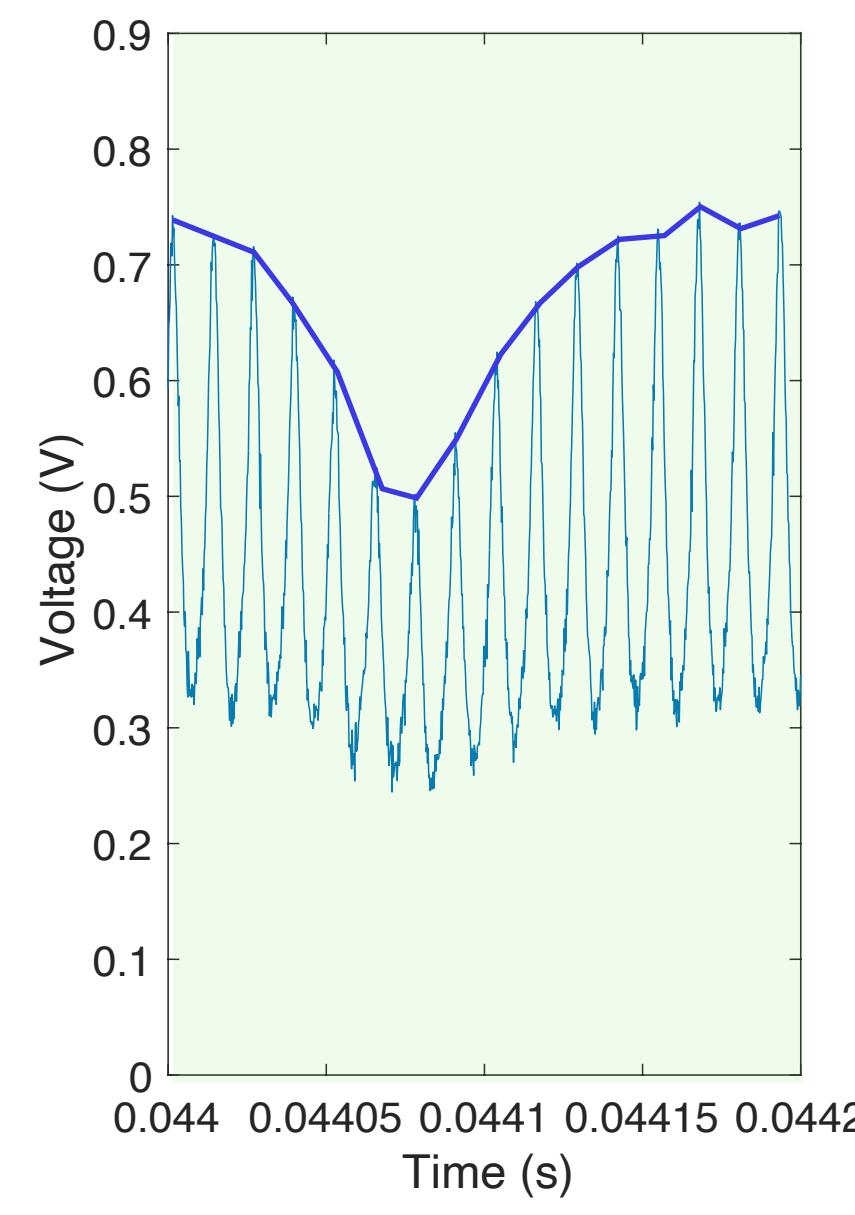
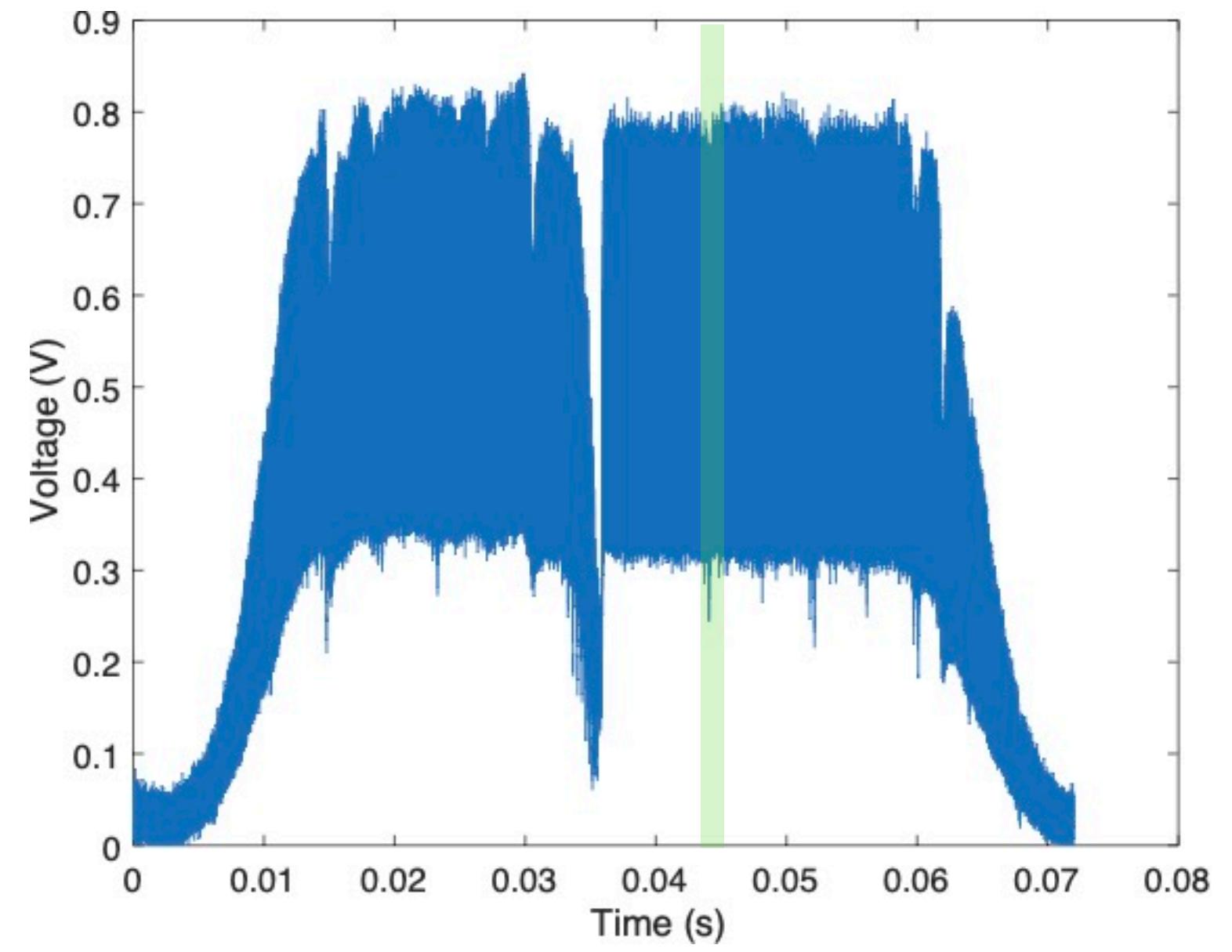
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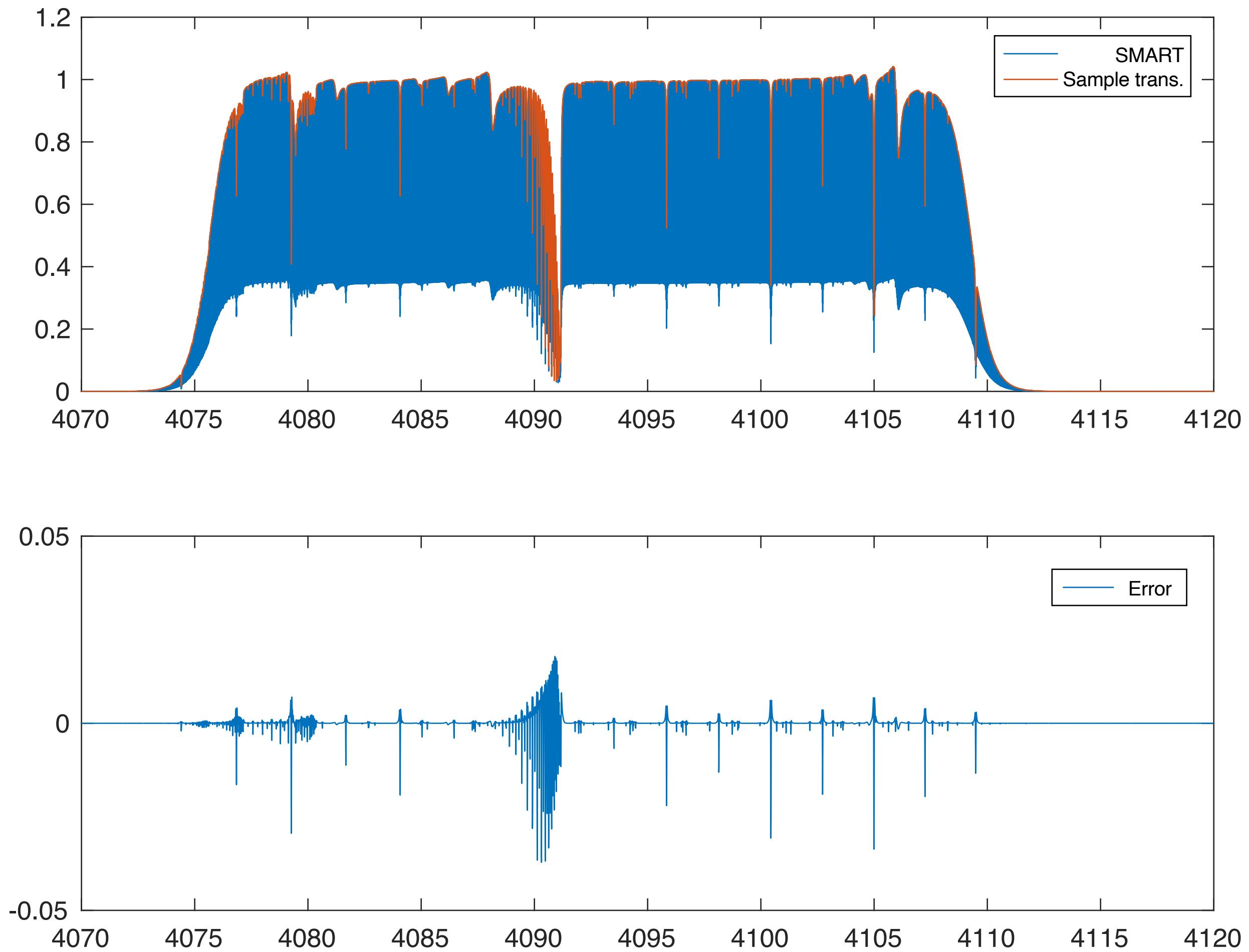
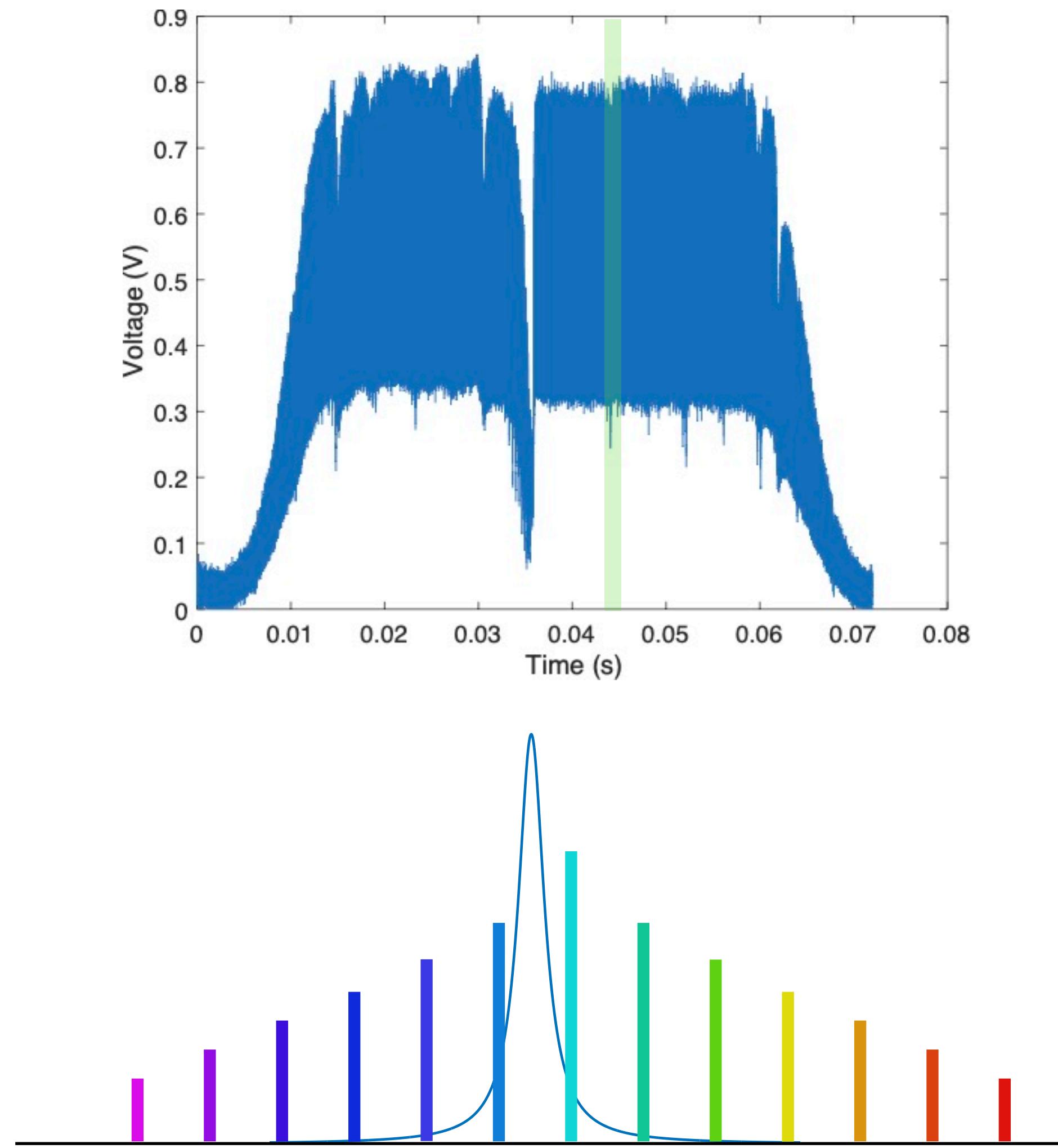
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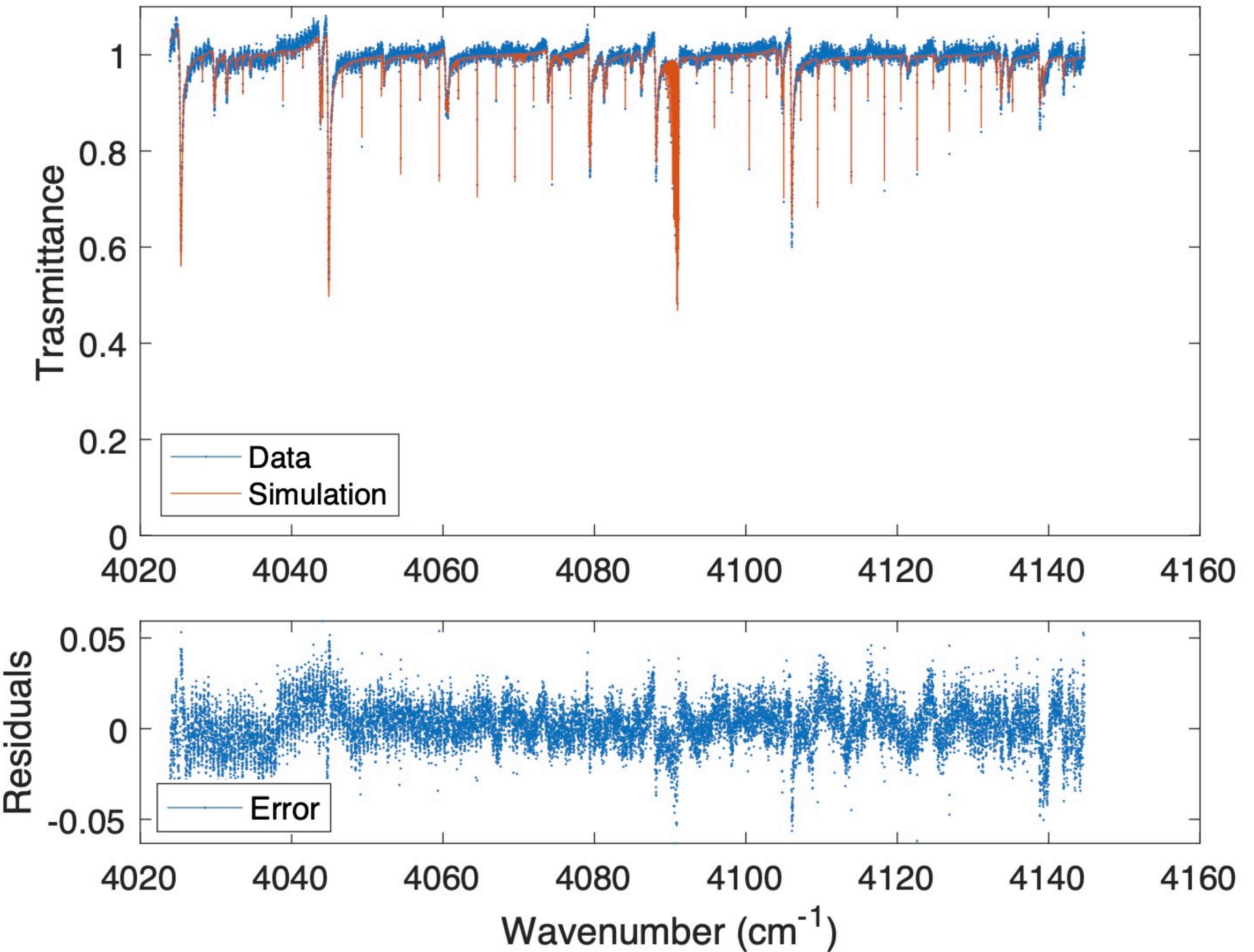


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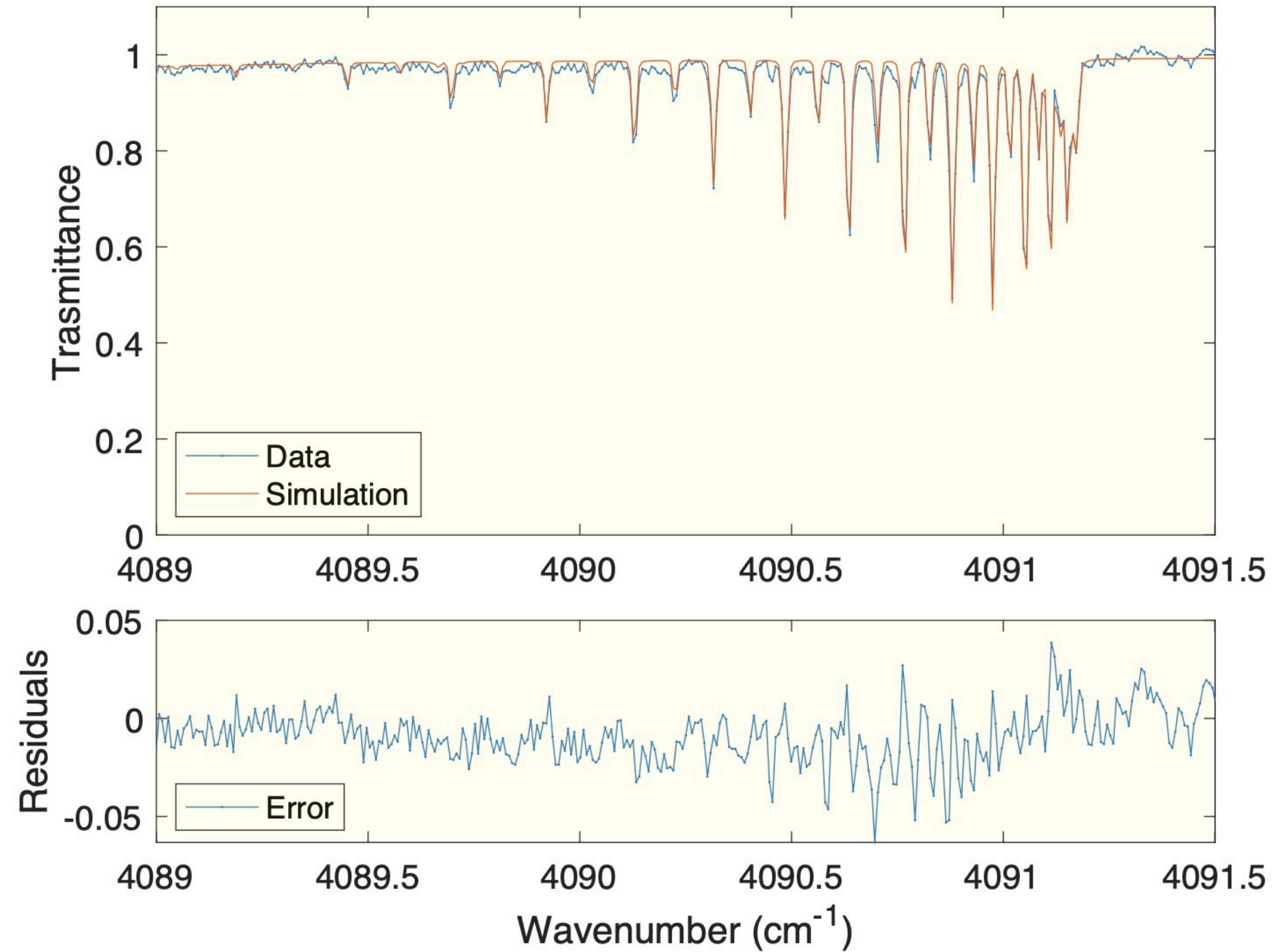
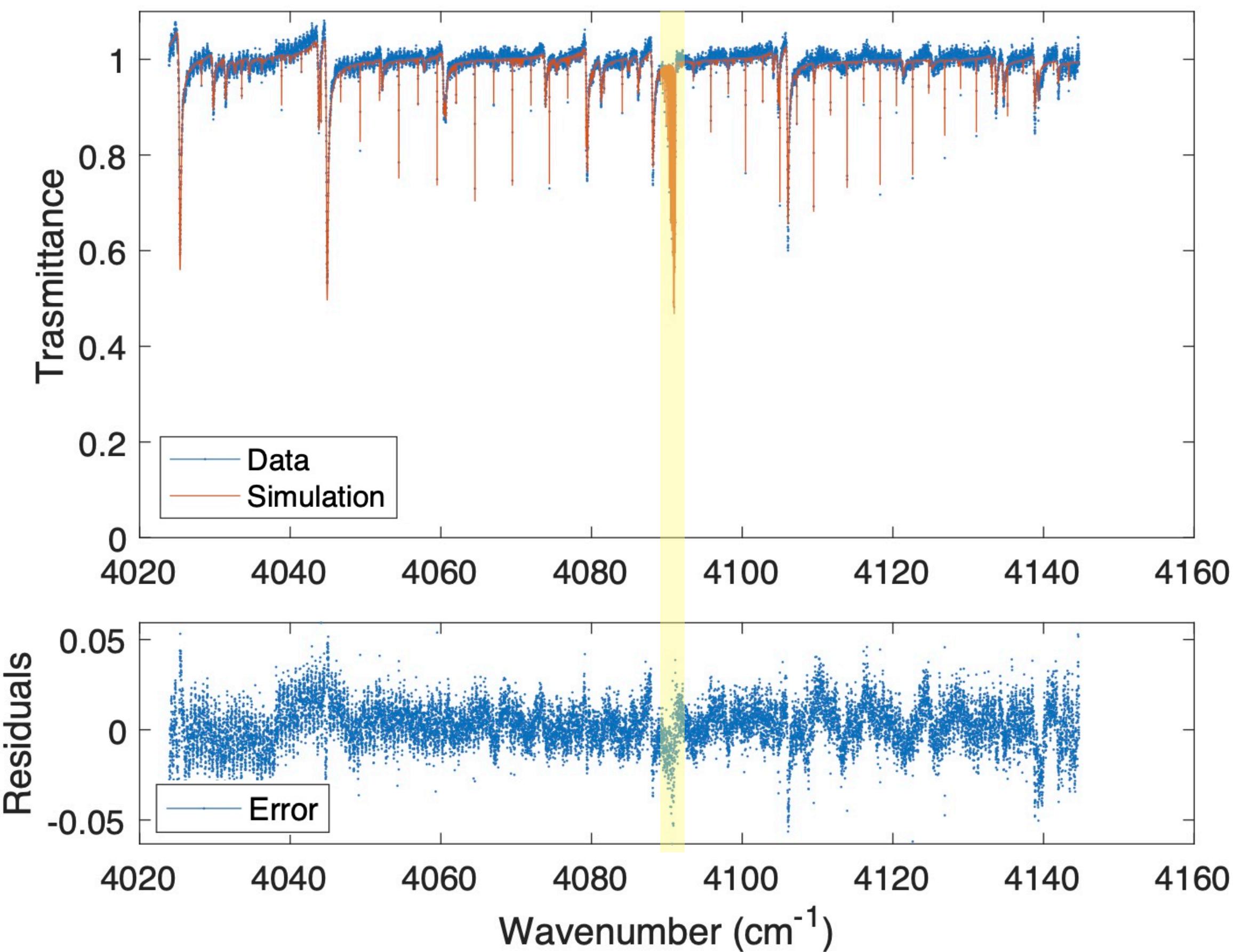


## Experimental results

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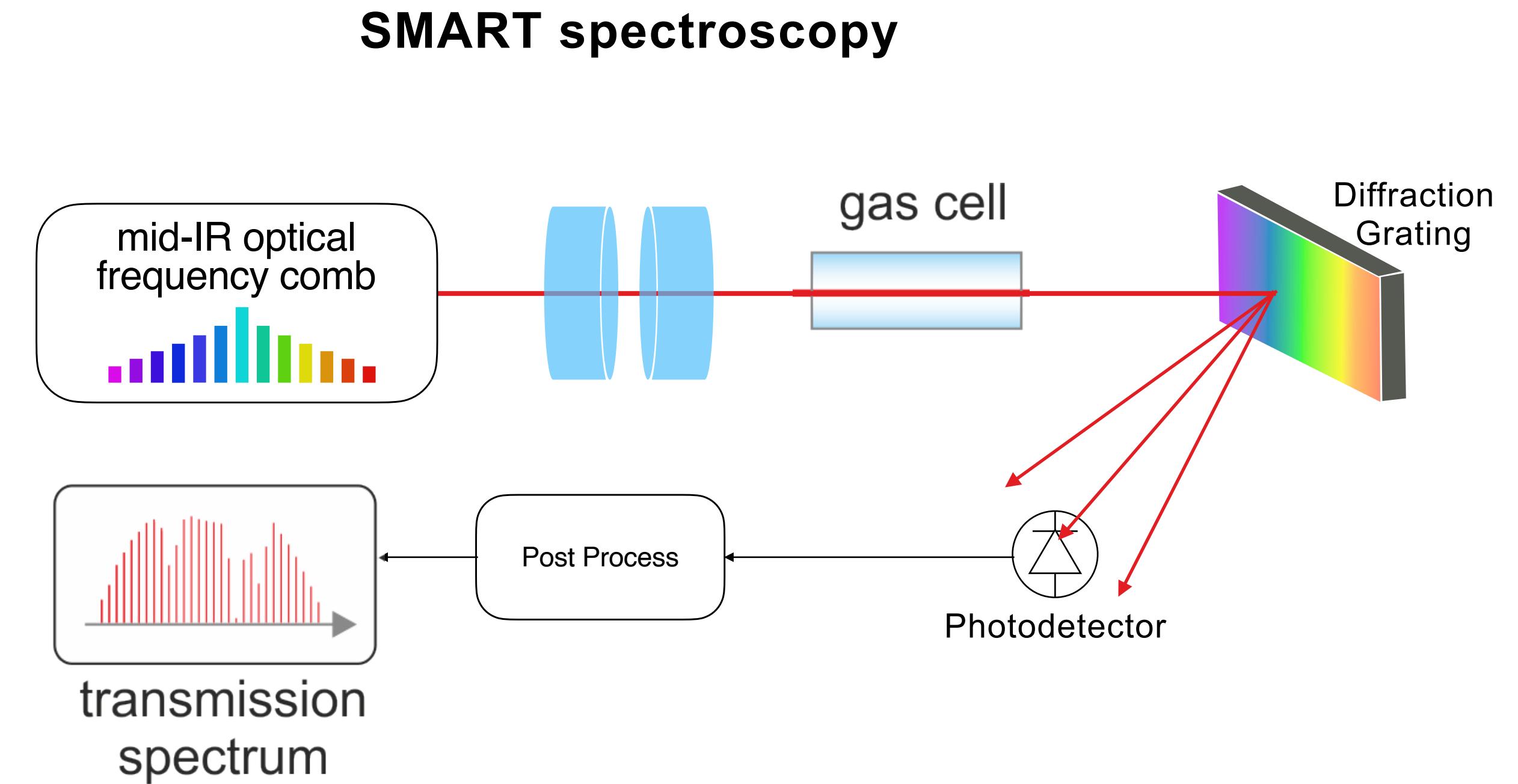
## Experimental results





## Conclusion

- High-resolution spectrometer at  $2.4 \mu\text{m}$
- Resolution: 220 MHz
- Bandwidth: 3.6 THz
- Measurement time: 400 ms

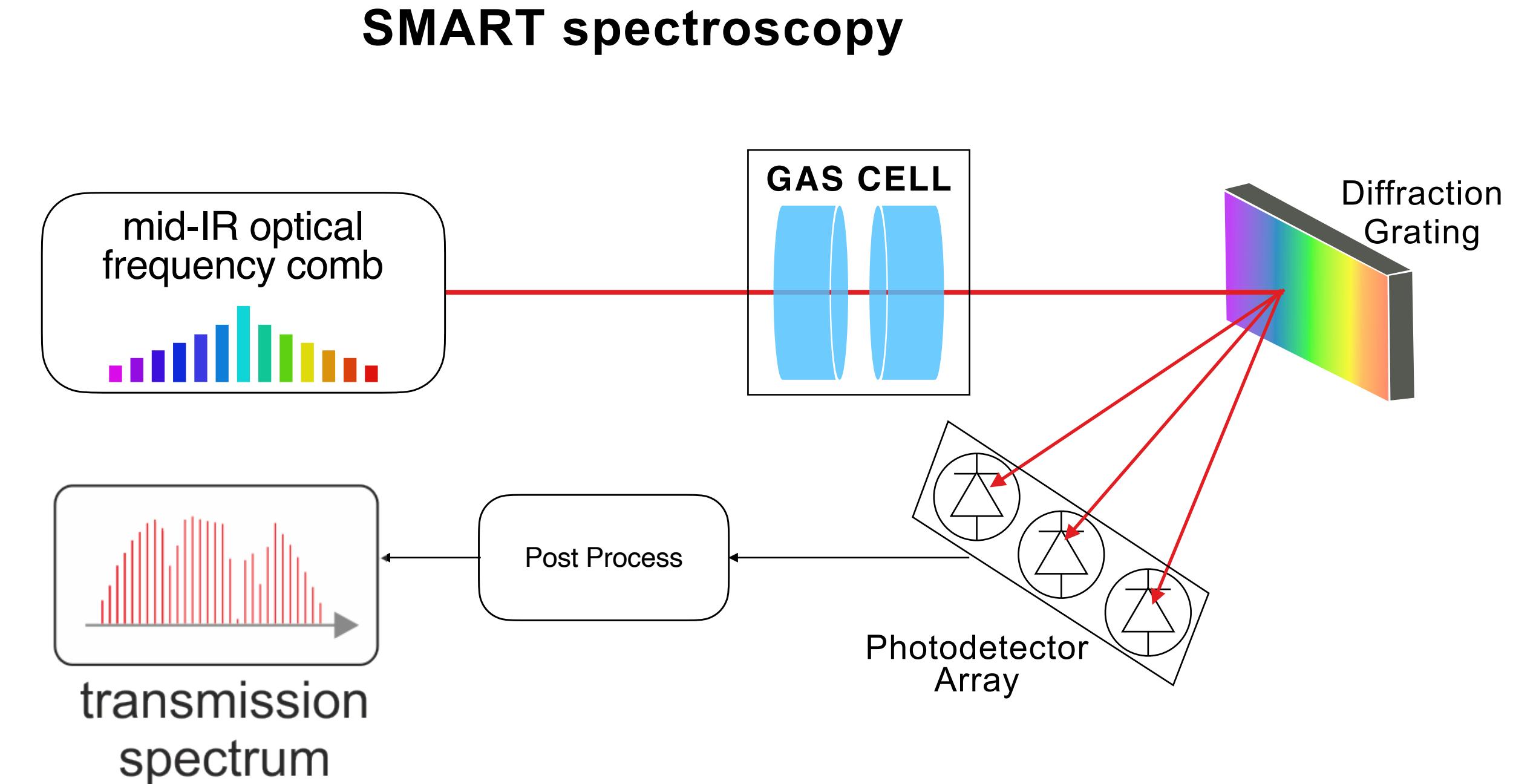


## Conclusion

- High-resolution spectrometer at  $2.4 \mu\text{m}$
- Resolution: 220 MHz
- Bandwidth: 3.6 THz
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## and future developments

- Increasing mirror finesse
- Detector array for parallel detection
- Cavity enhanced spectroscopy





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EDOARDO VICENTINI - 107° CONGRESSO NAZIONALE DELLA SIF



# 107° CONGRESSO NAZIONALE della SOCIETÀ ITALIANA DI FISICA

Thank you for your attention