Fourier Synthesis of Optical Waveforms

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Overview

- Introduction to Pulse Shaping
- Our Approach
  - Phase locking to an optical frequency comb
- Demonstration
  - 100 GHz waveforms
- Future directions
- Conclusion

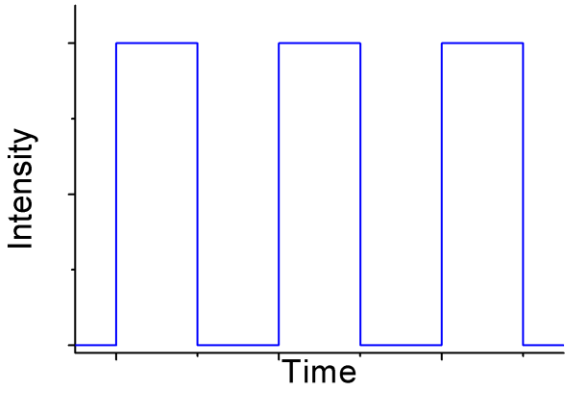
Introduction to Pulse Shaping

Optical Pulse Shaping

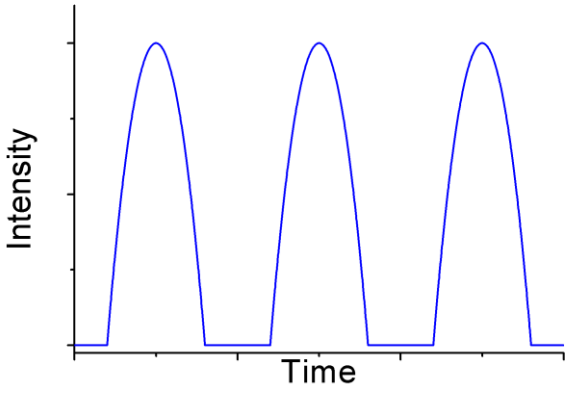
Refers to customising the shape of optical pulses in the temporal (and spectral) domain

Examples:

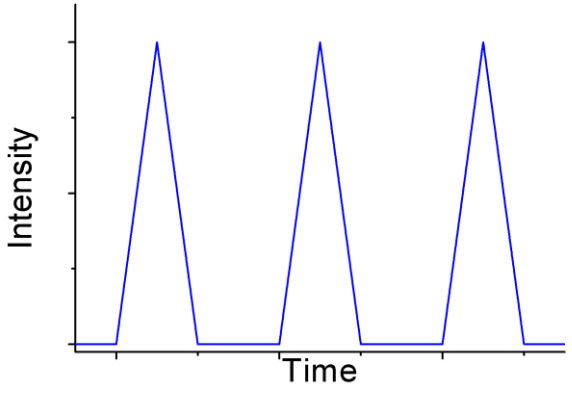
Rectangular



Parabolic



Triangular



Optical Pulse Shaping

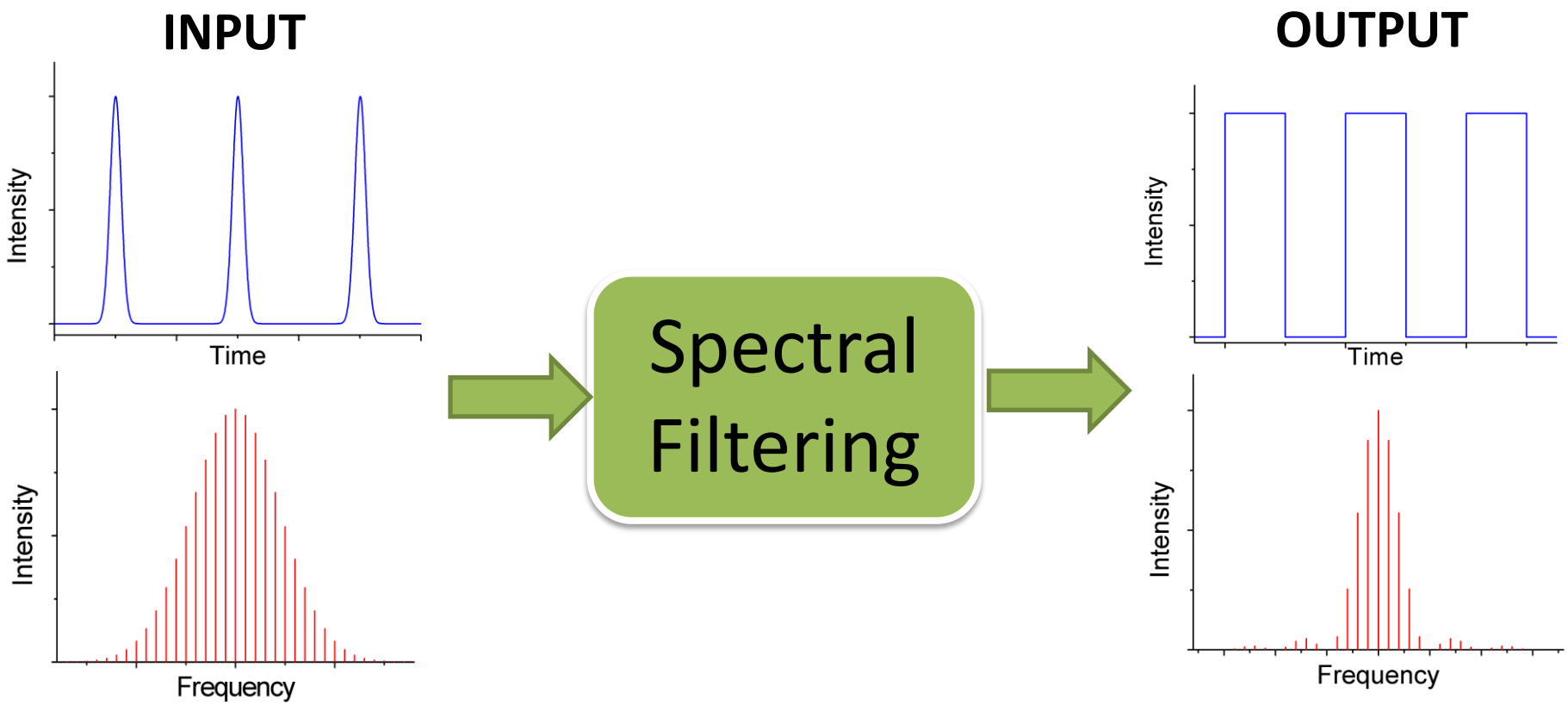
Applications for shaped optical pulses

- Optical signal processing
    - wavelength conversion
    - Pulse retiming
- Coherent control
    - chemical reactions
- General optical tool
    - Similar to RF arbitrary waveform generator

Optical Pulse Shaping

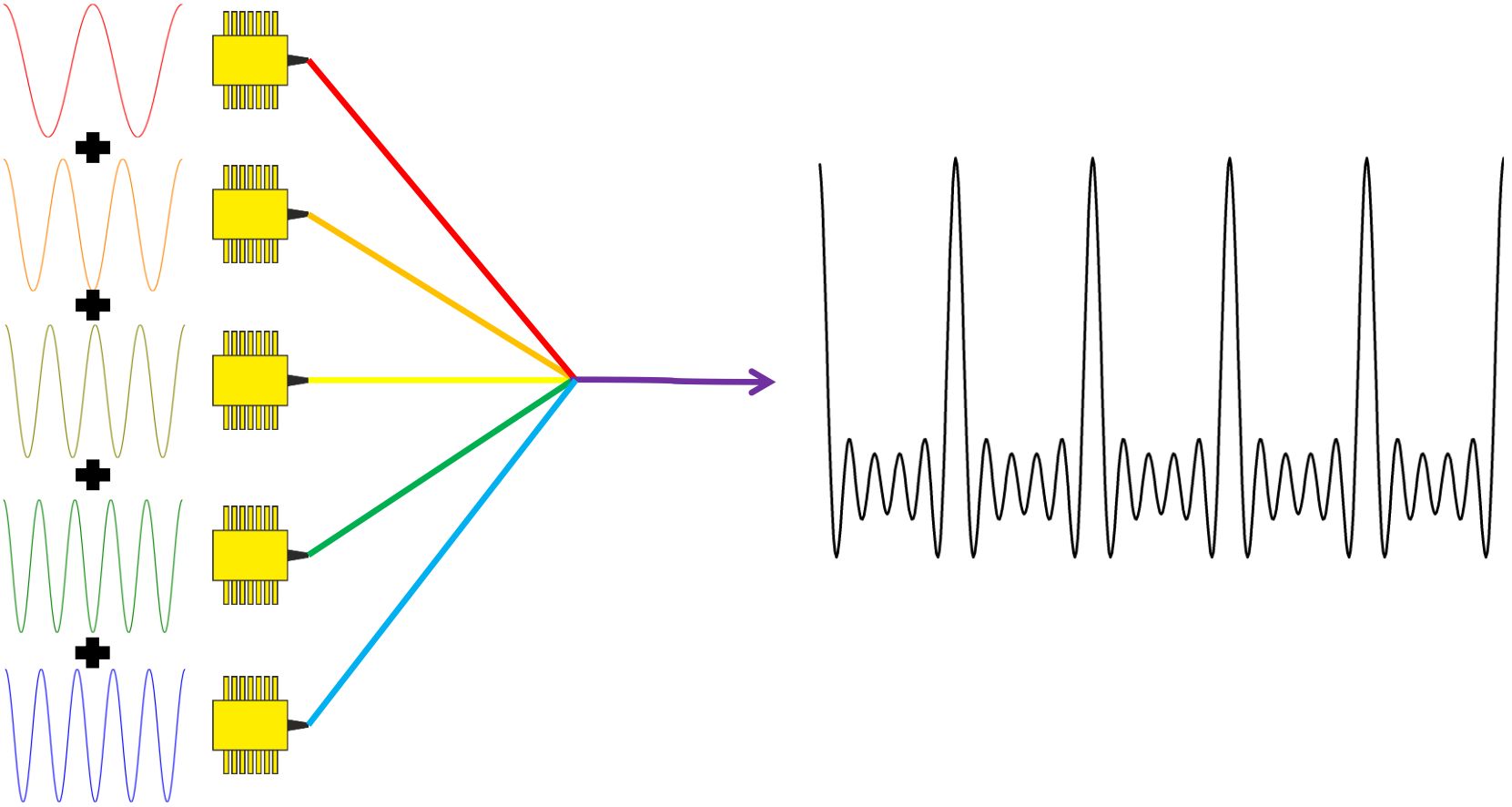
Traditionally done by spectral filtering

- Re-shaping pre-generated pulses into desired waveform



Fourier Synthesis

Build up pulses by combining many continuous wave lasers with different frequencies



Fourier Synthesis

Advantages

- ✓ Tunablility of repetition rate
- ✓ High power
  - Limited by power of each laser
- ✓ High optical signal to noise ratio (OSNR)
- ✓ Highly energy efficient
  - Only generate required components

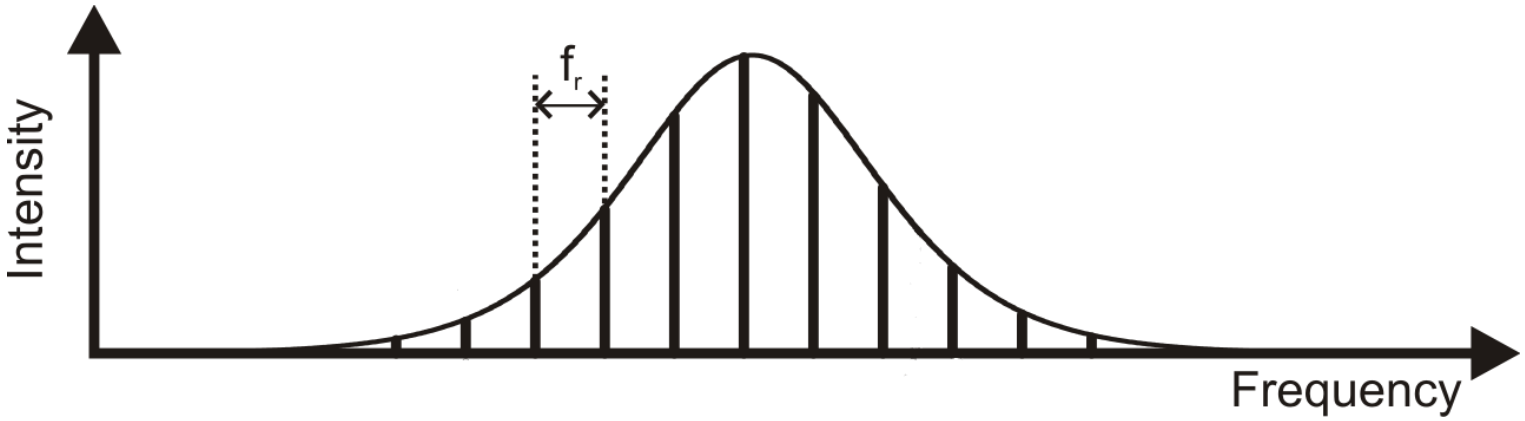
Disadvantages

- × Precise frequency spacing
- × Coherence between lasers required
- × Cost/complexity
  - 1 laser + various components required per frequency mode
  - Difficult to scale up

Our Approach: Phase locking to an optical frequency comb

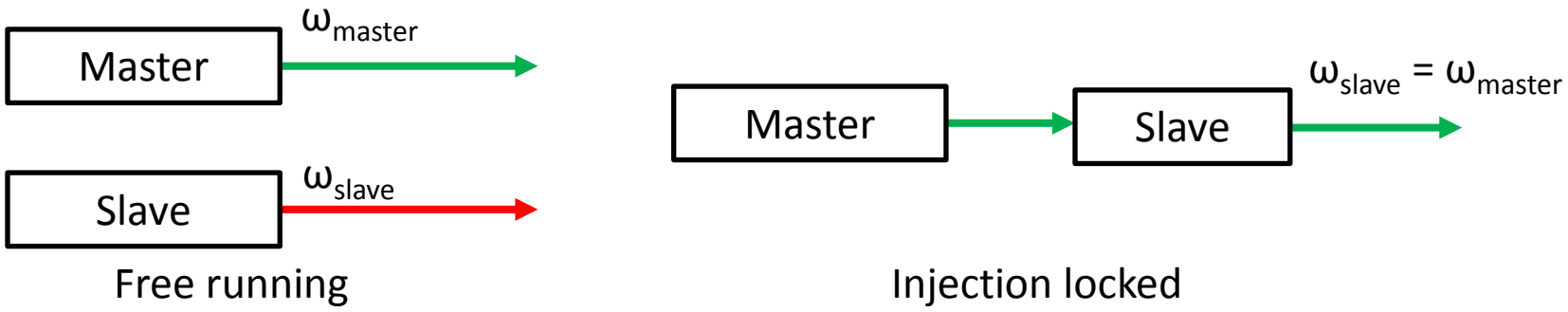
Optical Frequency Combs

- Combs have:
  - A large number of discrete modes – 'comb modes'
  - Constant frequency spacing
- Frequency comb can act as a 'frequency ruler' to ensure exact frequencies between lasers



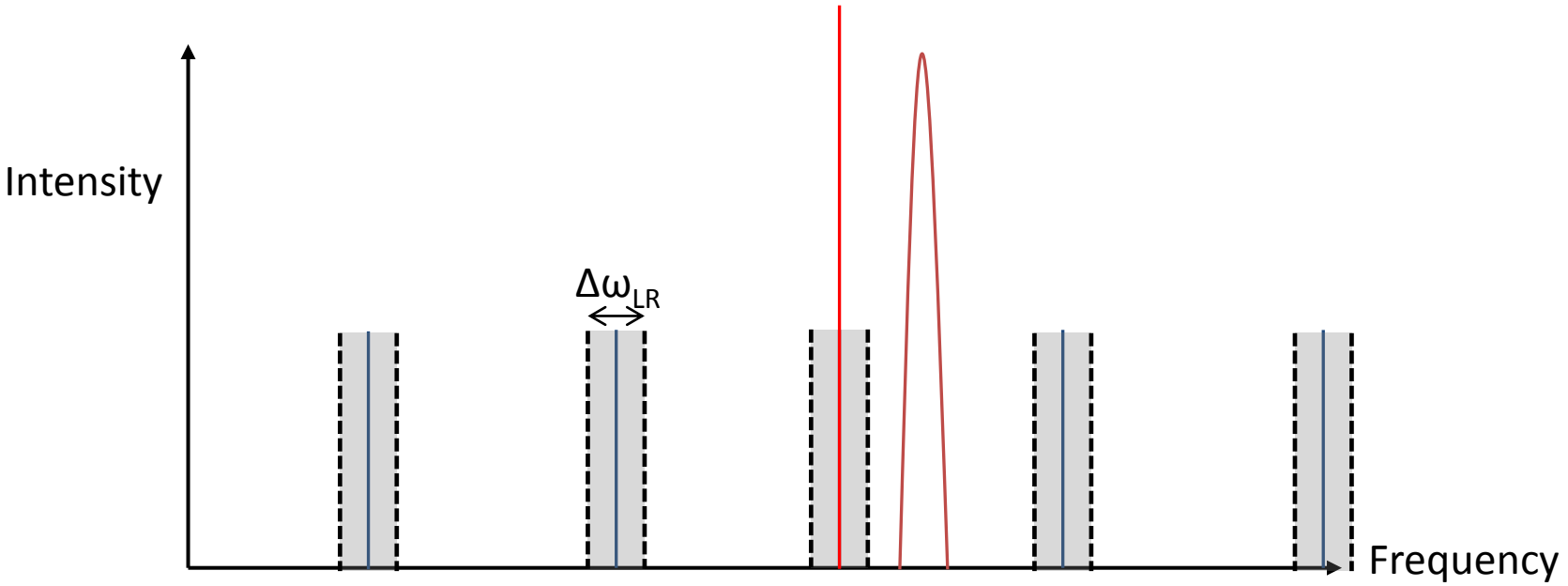
Optical injection locking

- One laser ('slave') adopts the frequency of another laser ('master') due to coupling



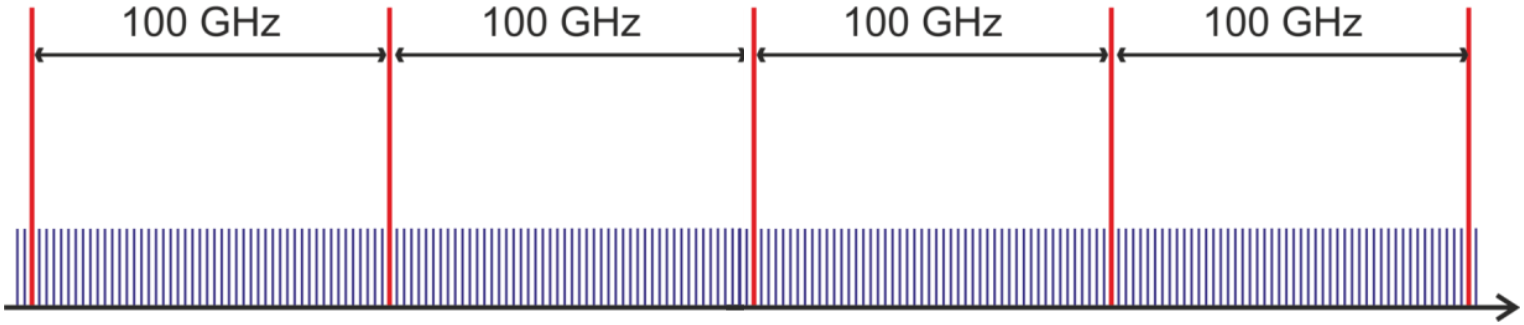
- Locking is maintained while the difference in free running frequencies is within the **locking range ($\Delta\omega_{LR}$)**

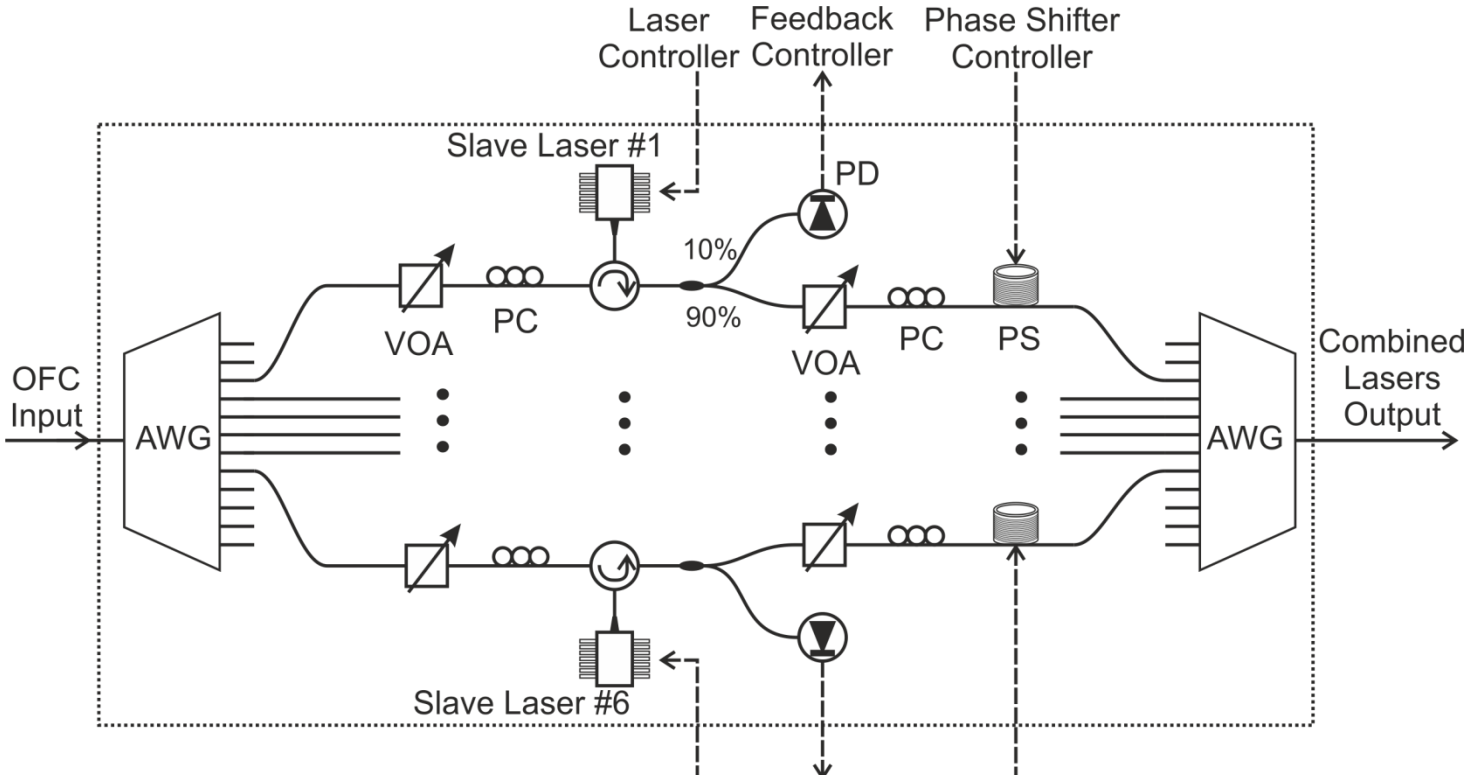
Injection locking to a frequency comb



D.S. Wu *et al.*, *"Direct selection and amplification of individual narrowly spaced optical comb modes via injection locking: design and characterization"*, Journal of Lightwave Technology, **31**(14), p. 2287, 2013

Experimental Set Up



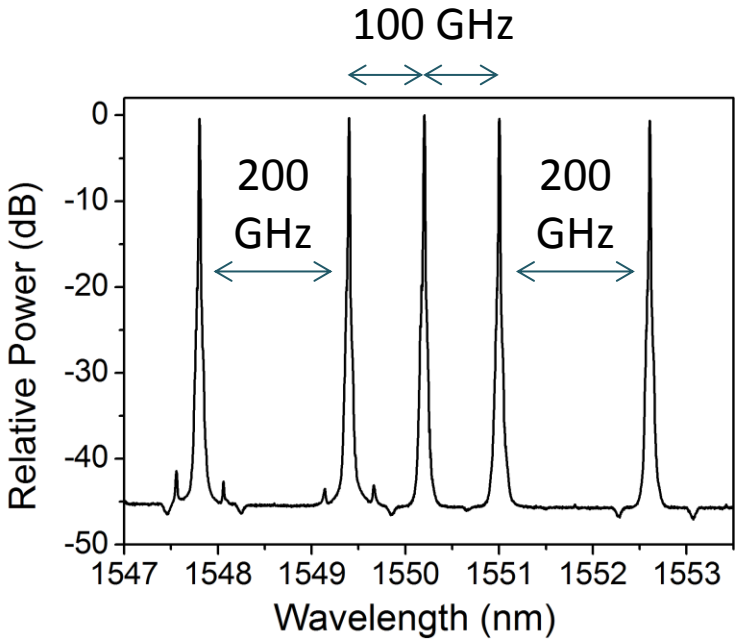


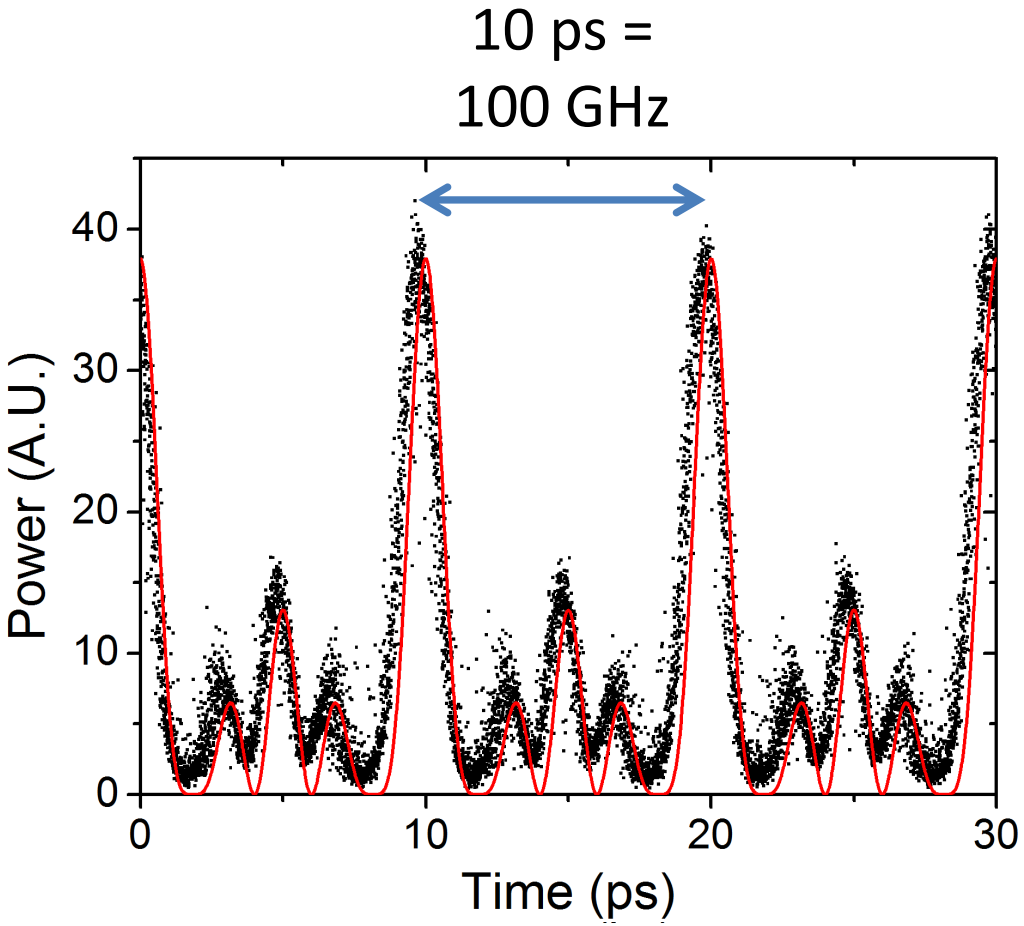
Measured waveforms using an optical sampling oscilloscope (500 GHz bandwidth)

Results

Results

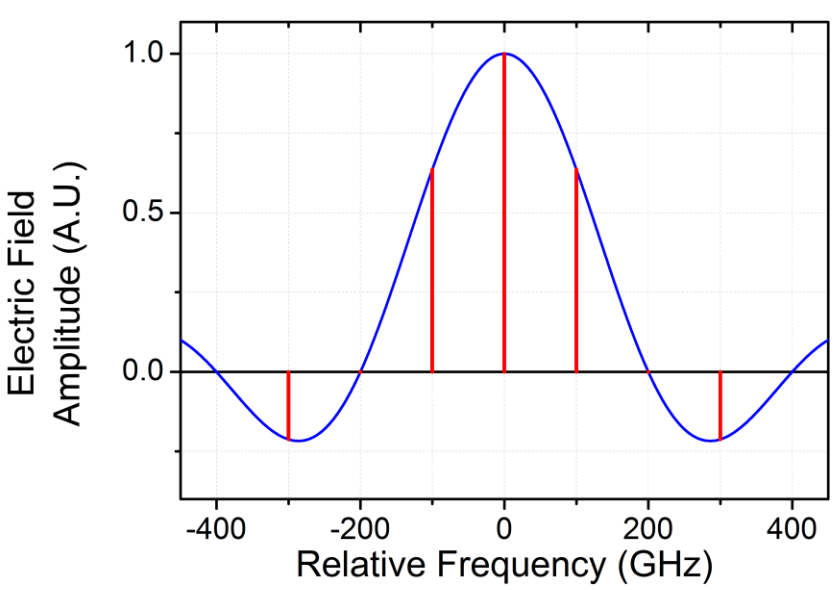
Pulses – Phase Alignment

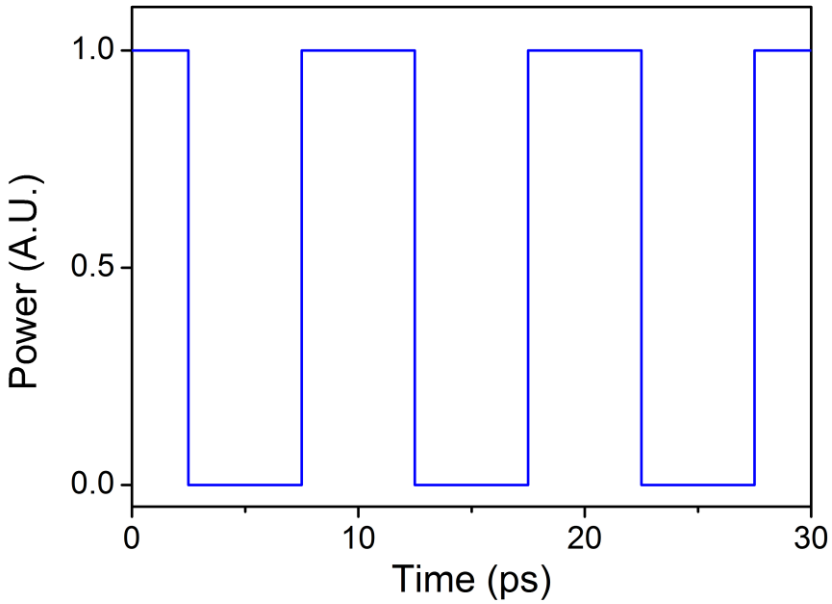




Results

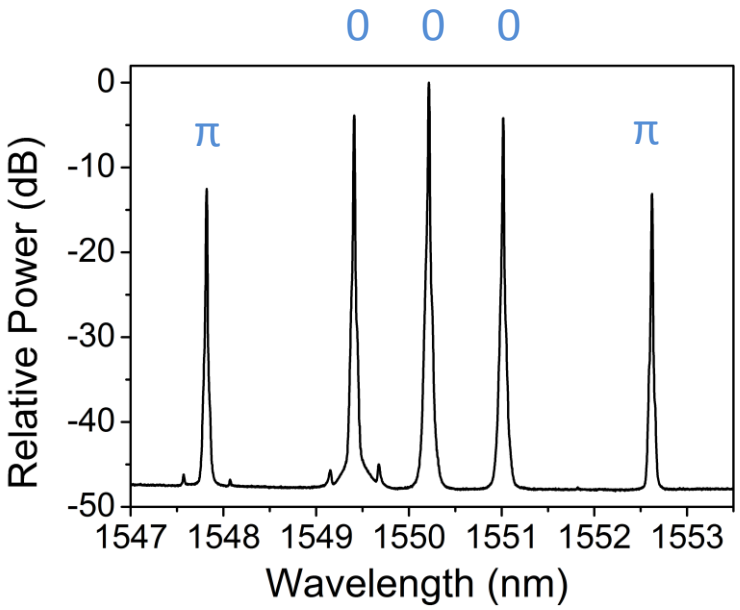
sinc-spectrum flat top pulses

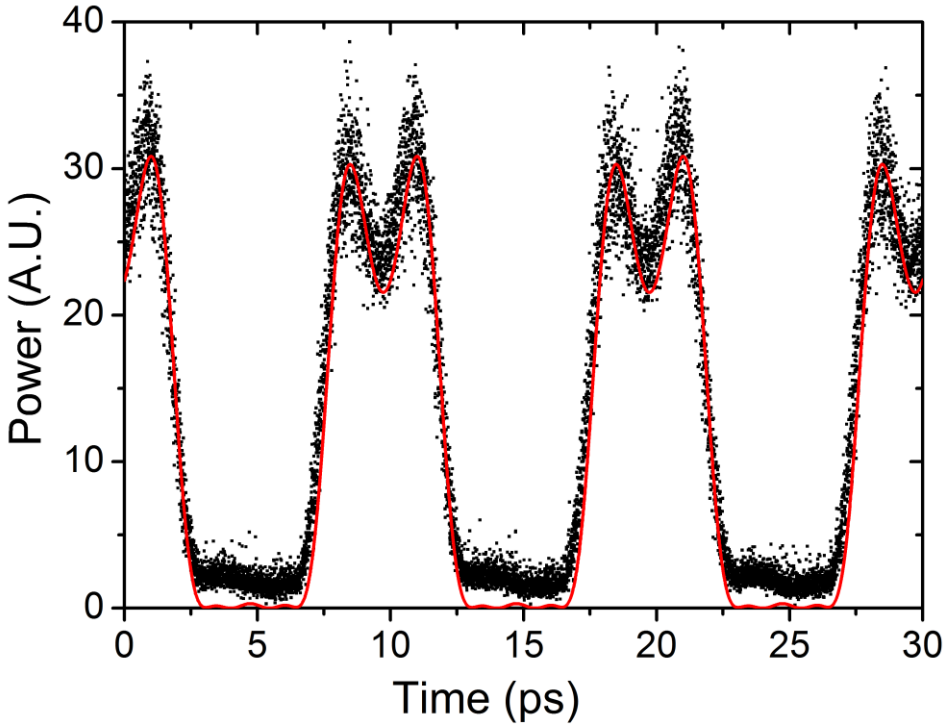




Results

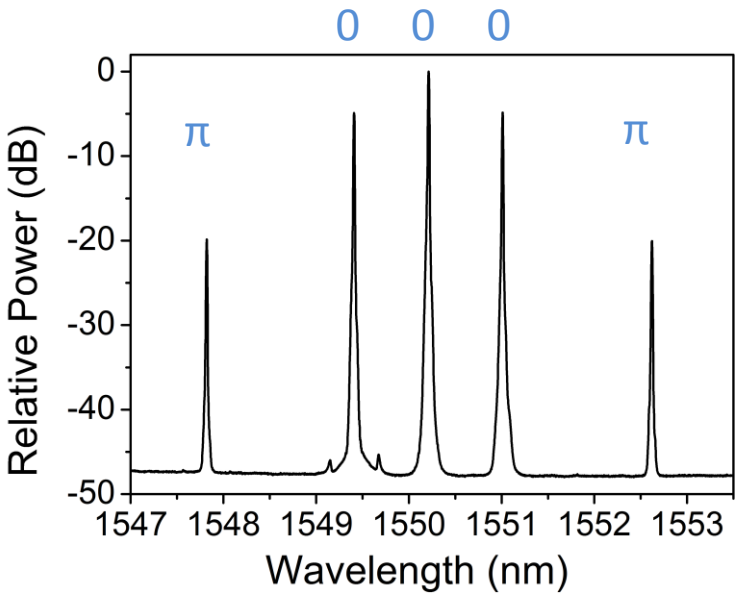
sinc-spectrum flat-top pulses

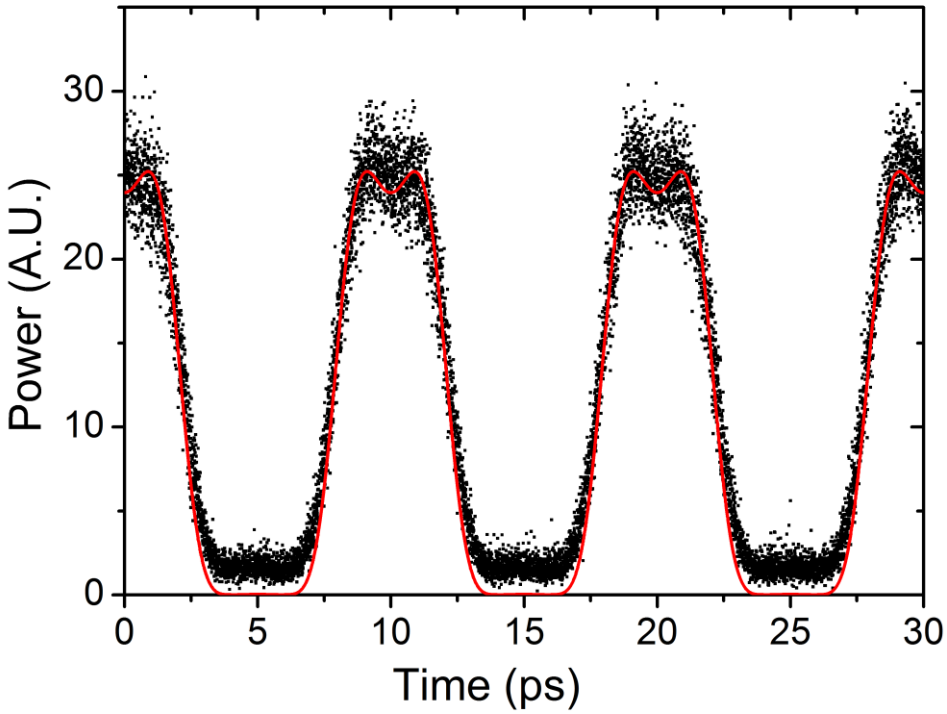




Results

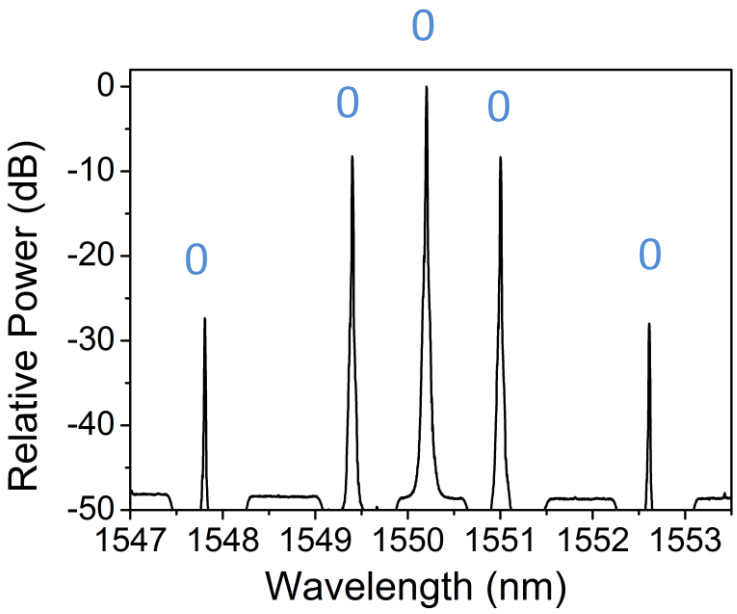
Apodised sinc-spectrum flat-top pulses

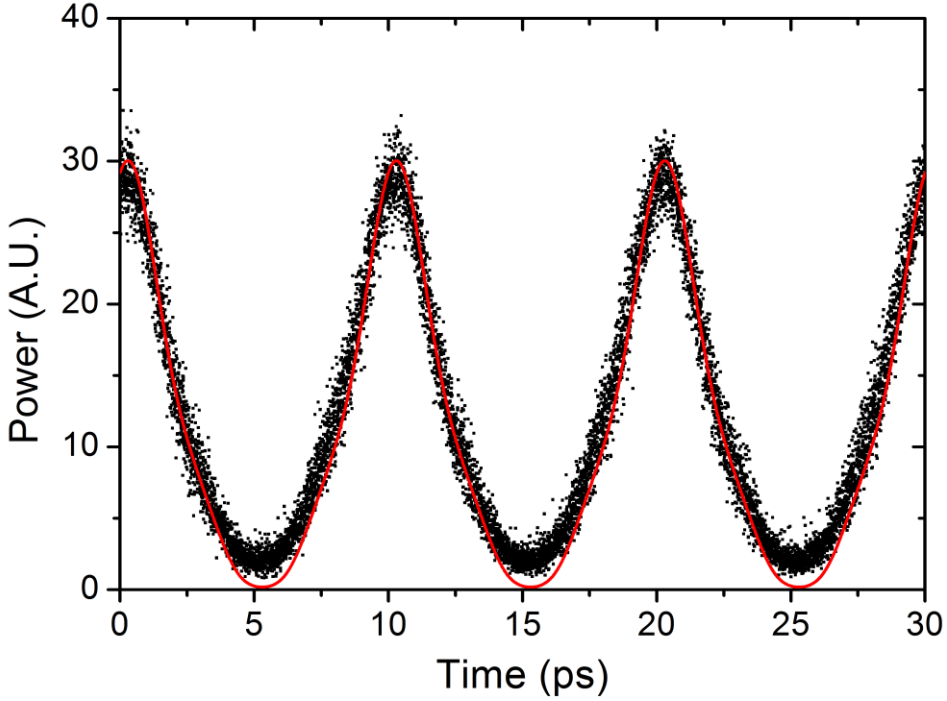




Results

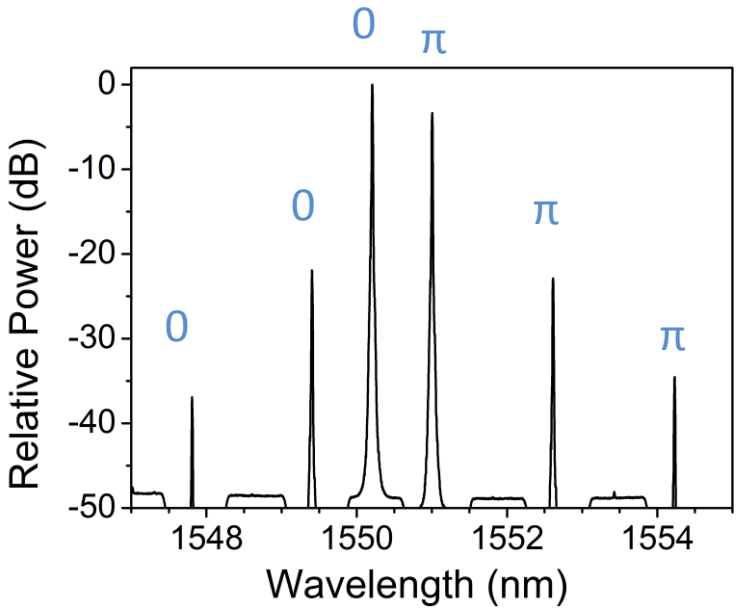
sinc^2-spectrum Dark-parabolic pulses

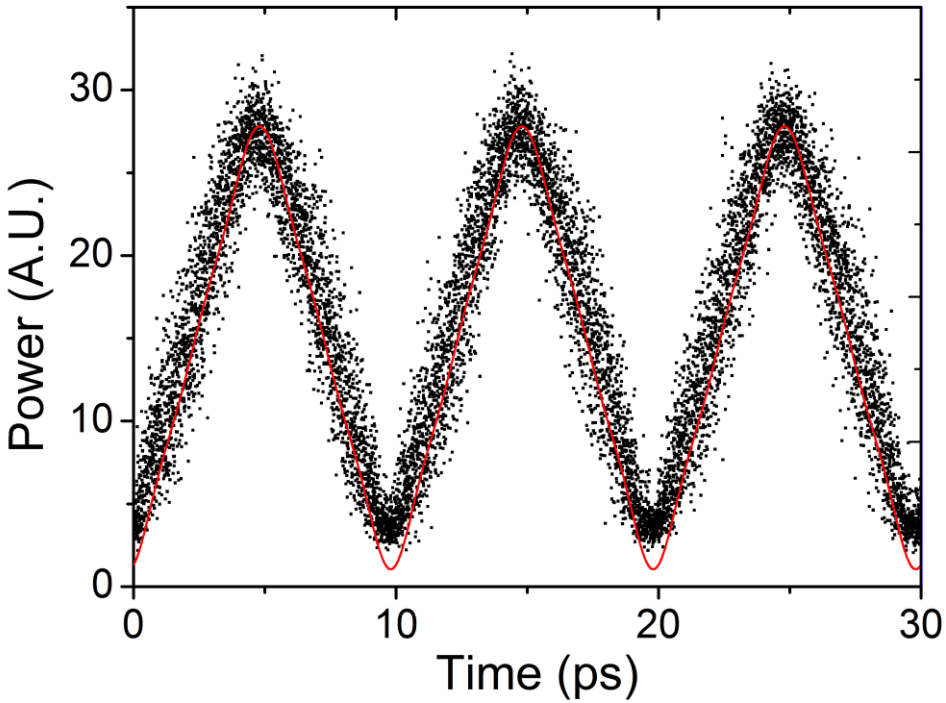




Results

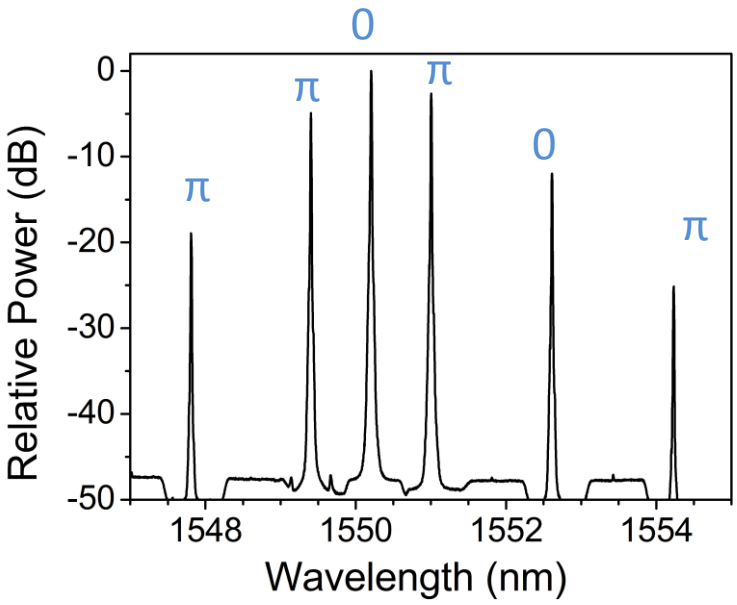
Triangular pulses

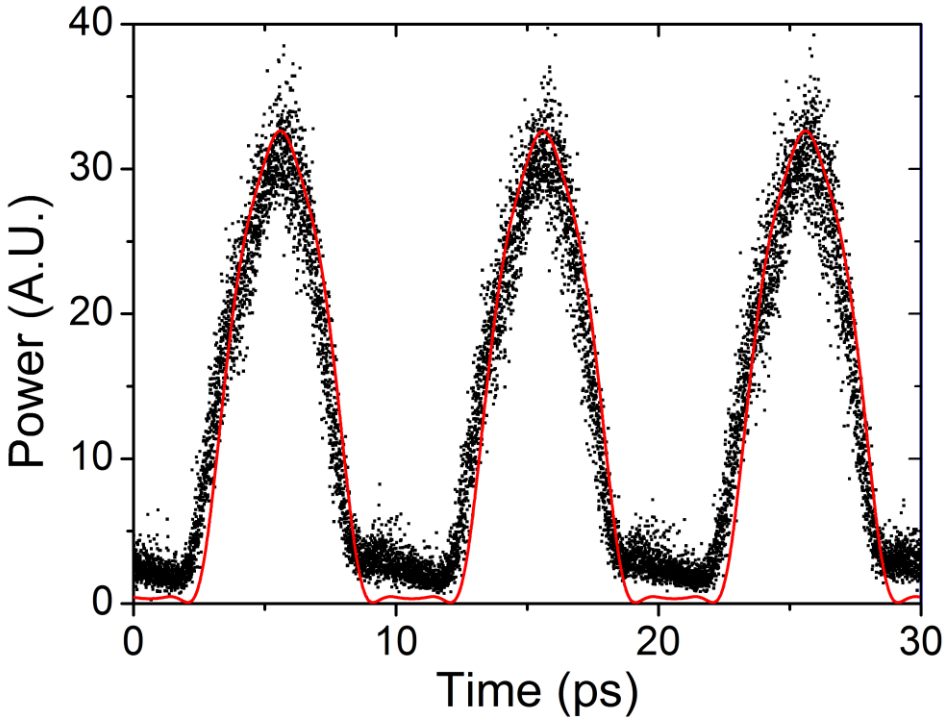




Results

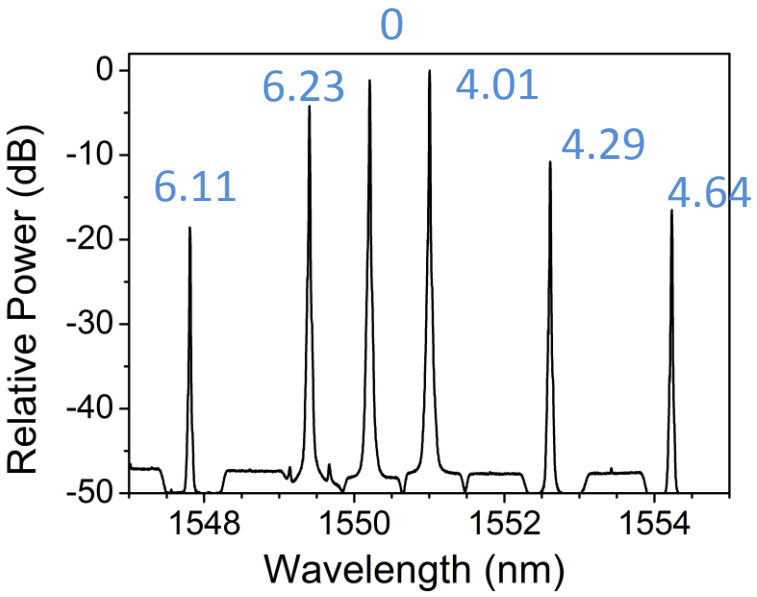
Bright Parabolic pulses

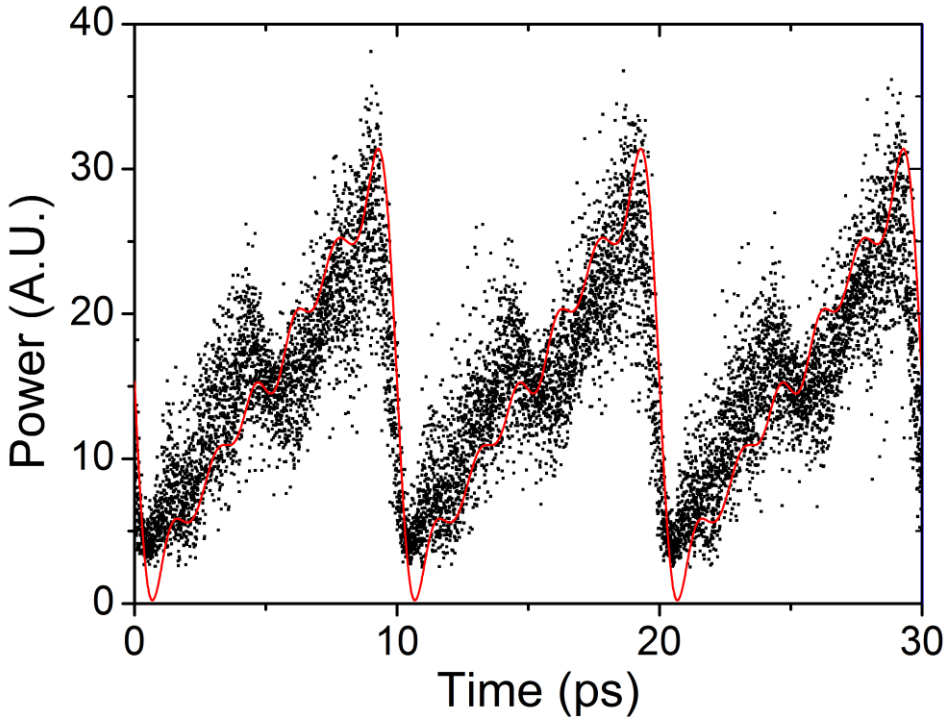




Results

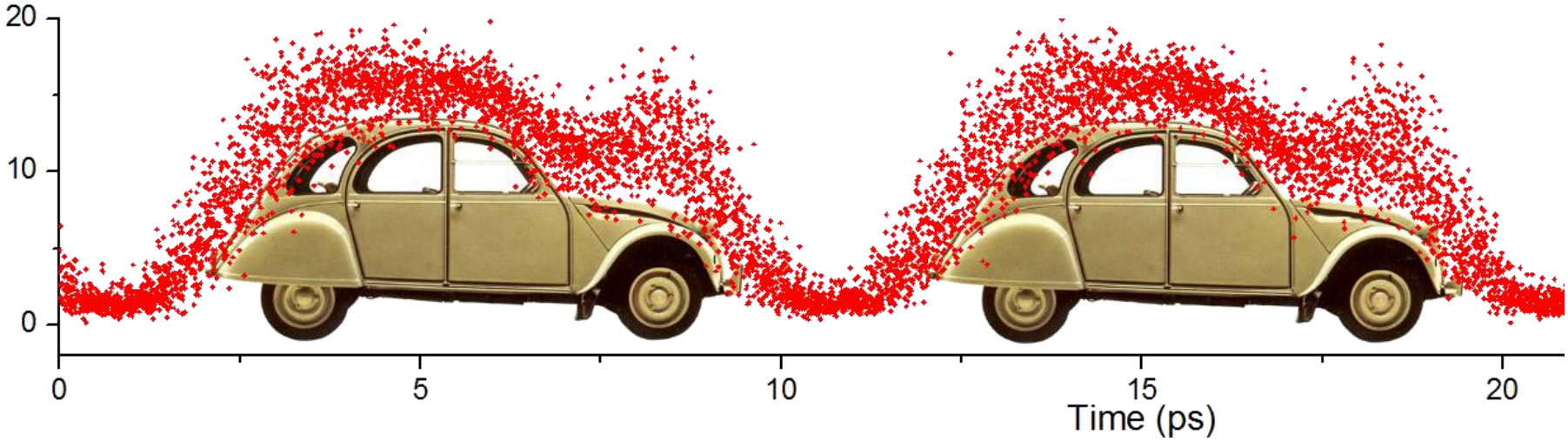
Sawtooth Pulse





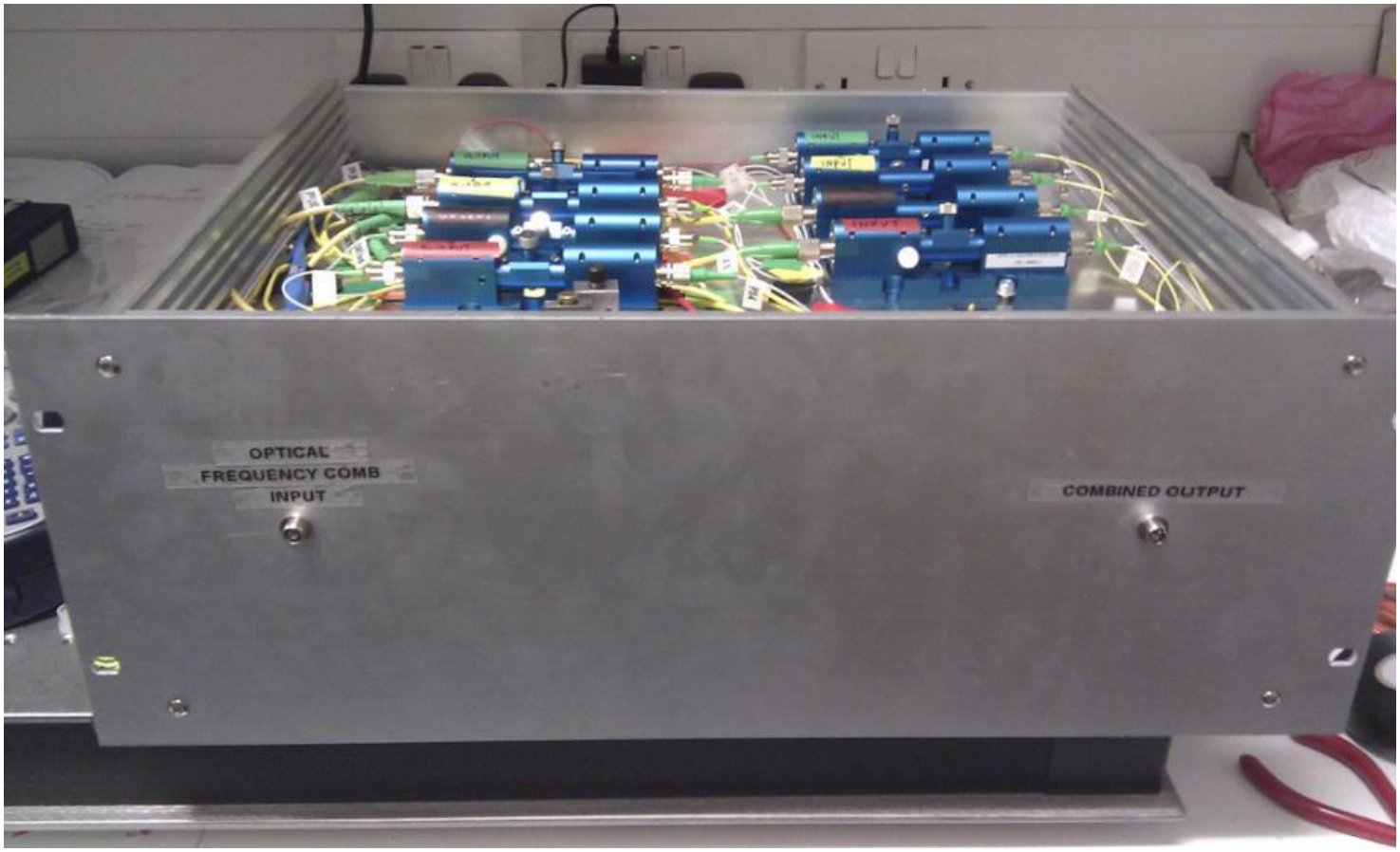
Results

Optical Citroën 2CV



Future plans

- More lasers
- Integrated device



Conclusion

Conclusion

- Optical Injection locking to phase lock semiconductor lasers to an optical frequency comb
- Fourier synthesis of optical waveforms by combining multiple locked lasers together
- With integrated optics can lead to a compact and useful device

The End

Thank you for your attention

Acknowledgements

Radan Slavík, David Richardson

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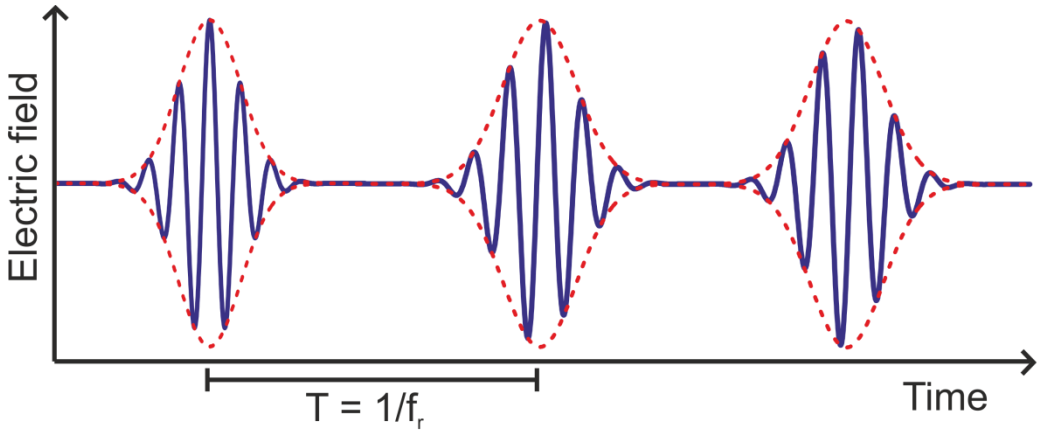
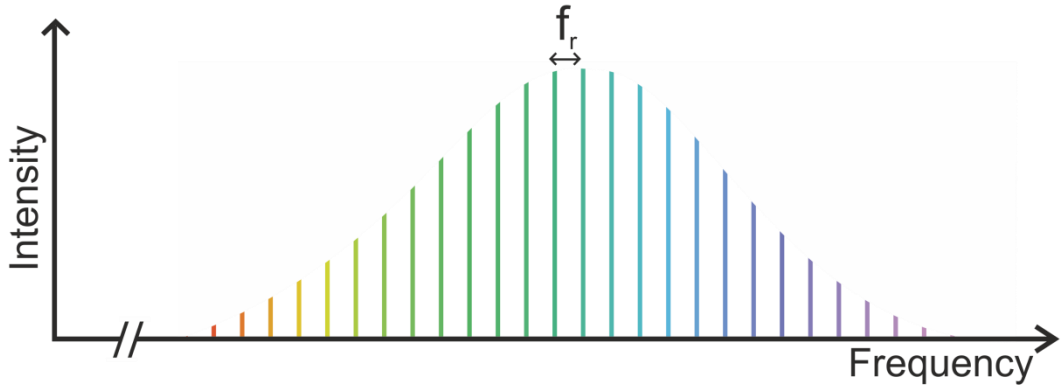
Fourier Transform

A periodic function can be decomposed into a series of sine and cosine functions

Temporal Domain



Frequency Domain



Line-by-line Pulse Shaping

- Disperse signal into different spectral components (e.g. gratings)
- Individually manipulate amplitude & phase of different components (e.g. spatial light modulator)
- Recombine spectral components

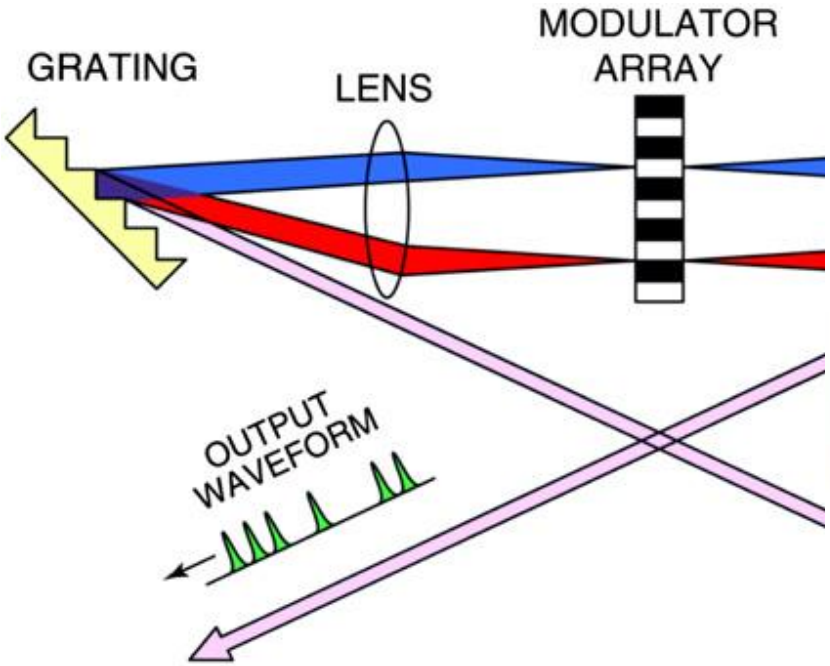
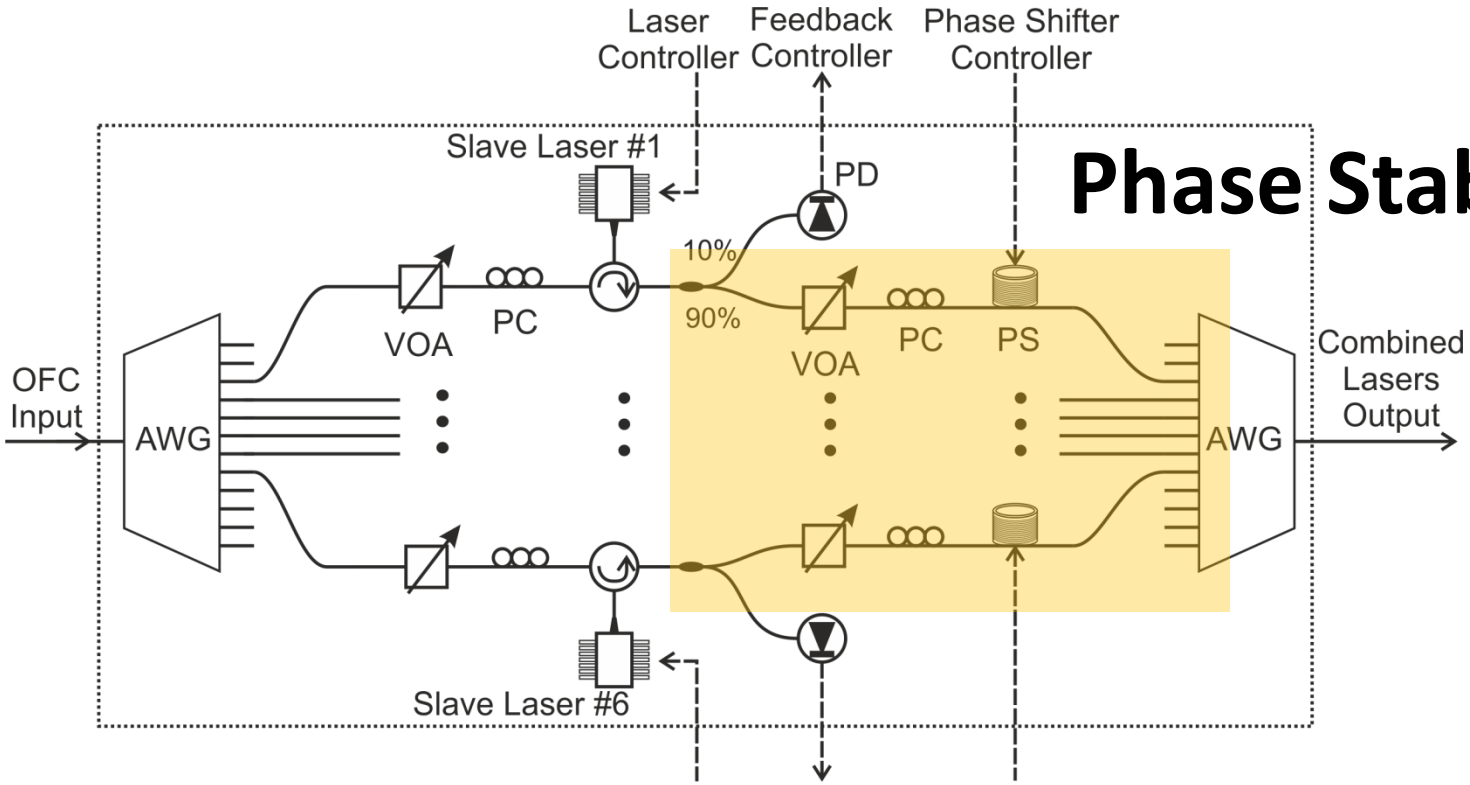
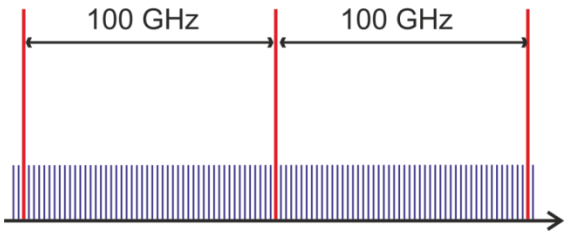


Image source: A.M. Weiner, “Ultrafast optical pulse shaping: A tutorial review," Optics Communications, 284(15), 2011.

Experimental Set Up

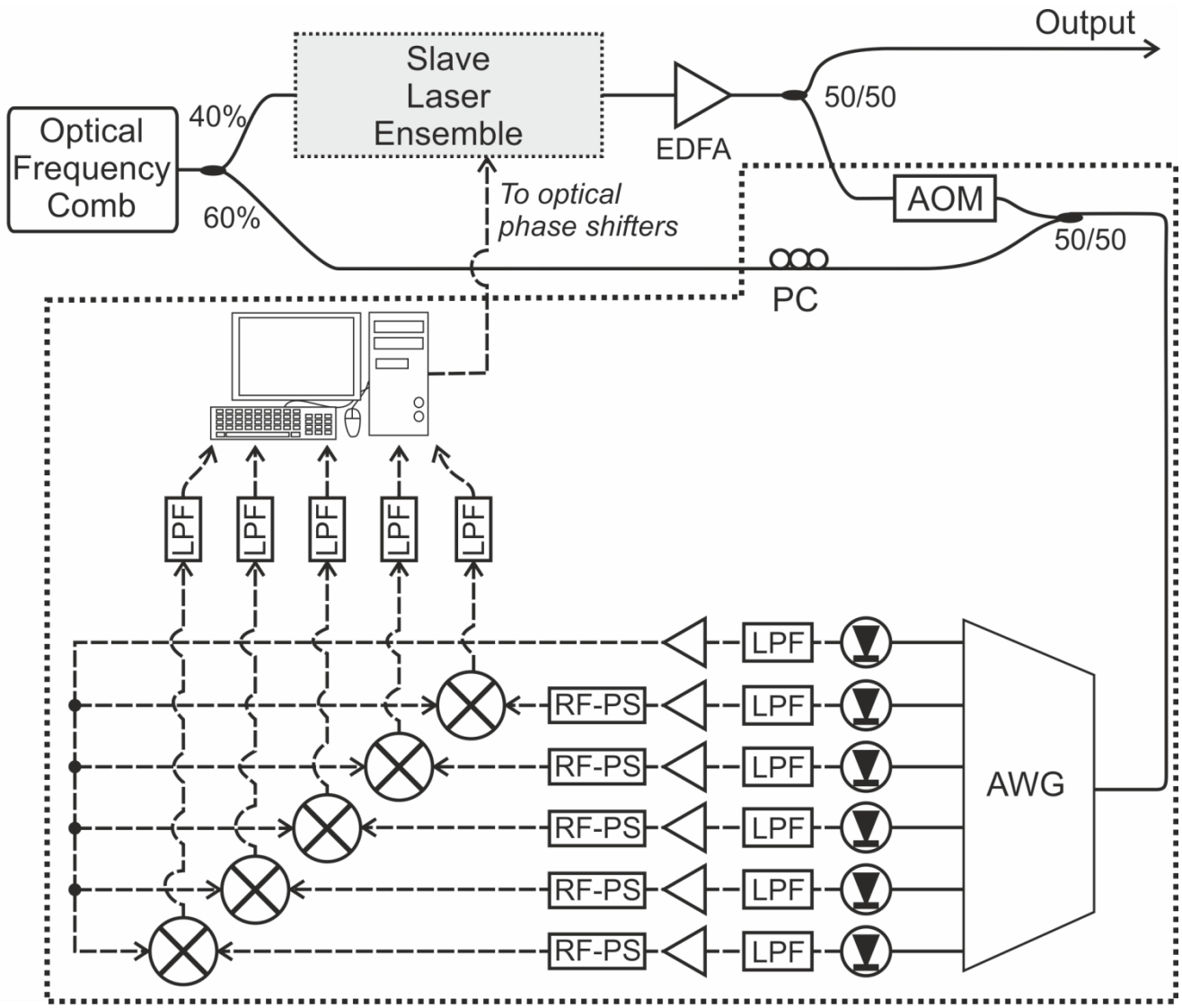


Phase Stabilisation

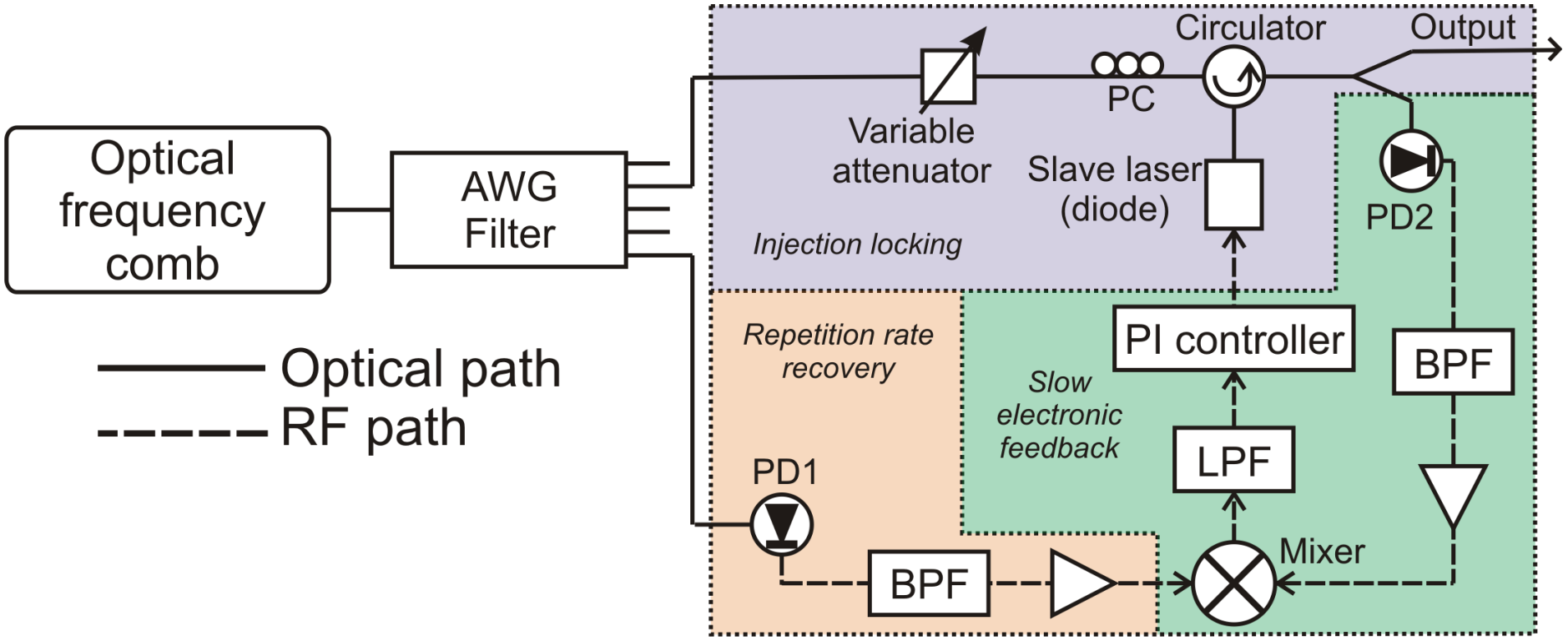


Measured waveforms using an optical sampling oscilloscope (500 GHz bandwidth)

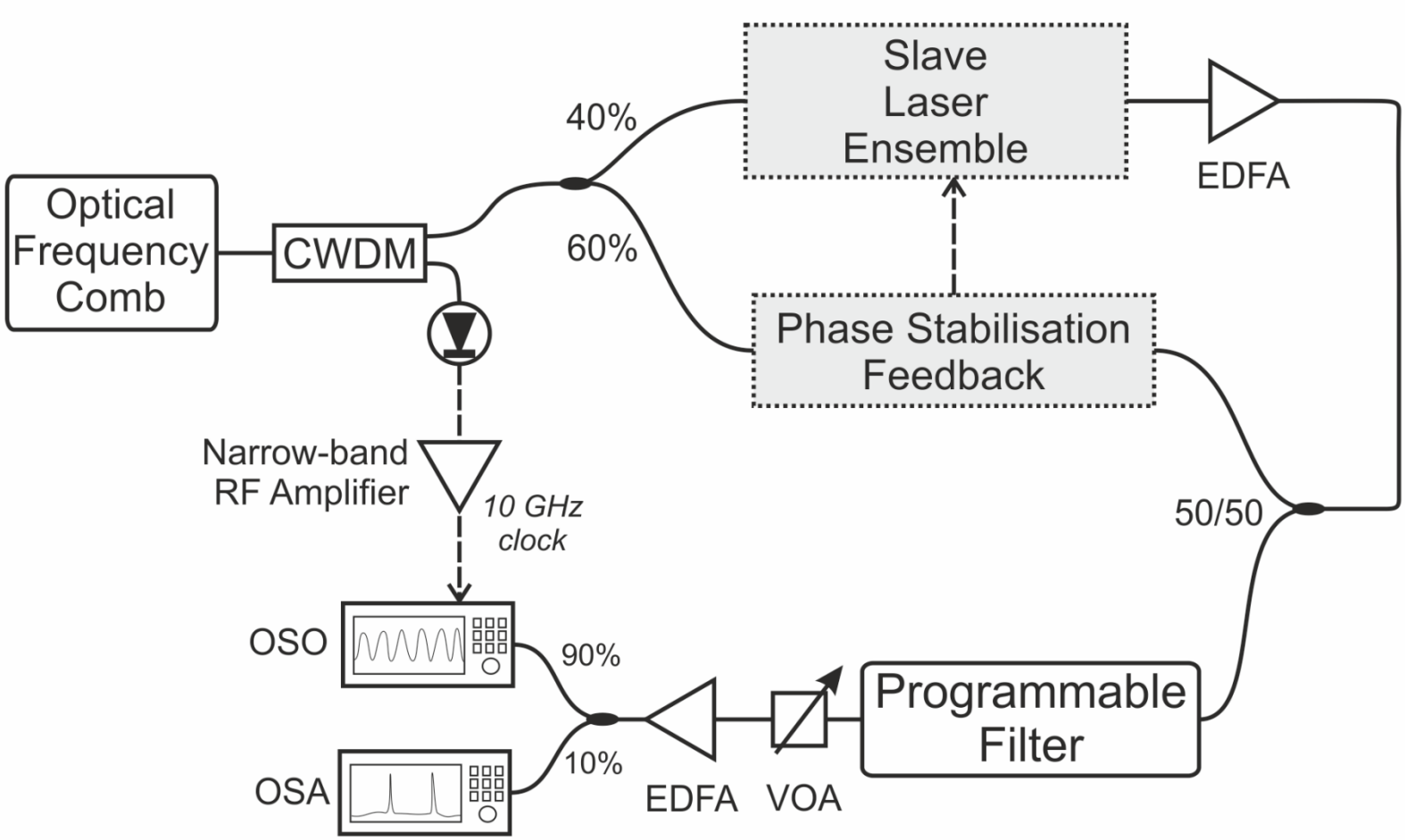
Phase stabilisation



Optical Injection Phase Lock Loop



Fourier Synthesis



Previous results

Using a 250 MHz spaced comb with semiconductor slave lasers:

- Characterised the short- and long- term stability
  - Frequency variation Allan deviation: 4.4×10^{-19} at 1000 s [1]
  - Phase noise: 0.02 rad^2 (measurement bandwidth 100 Hz – 500 MHz) [2]

1. D.S. Wu, et al. "Robust optical injection locking to a 250 MHz frequency comb without narrow-band optical pre-filtering," *2011 CLEO Pacific Rim*.
2. D.S. Wu, et al. "Phase noise and jitter characterization of pulses generated by optical injection locking to an optical frequency comb," *Frontiers in Optics* 2012.