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$LiNbO_3$ Nanophotonic Platform for Nonlinear Optics

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NNCI Etch Symposium, 2022

Thin-film lithium niobate: an excellent nonlinear optical platform

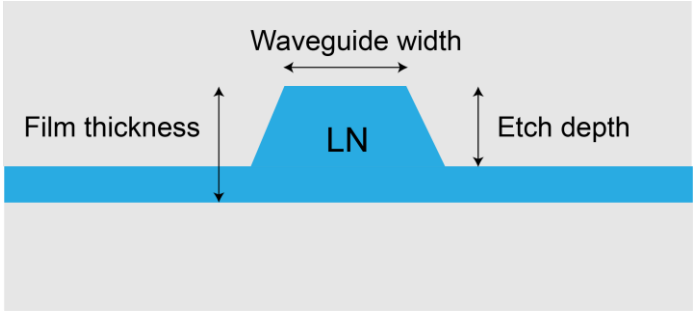
$$\boldsymbol{P}(t) = \epsilon_0\left(\chi\boldsymbol{E}(t) + \chi^{(2)}\boldsymbol{E}^2(t) + \chi^{(3)}\boldsymbol{E}^3(t) + \cdots\right)$$

Lithium niobate

- Large electro-optic effect, $\chi^{(3)}$ nonlinearity (+ more)
- Large transparency window
- Periodic poling

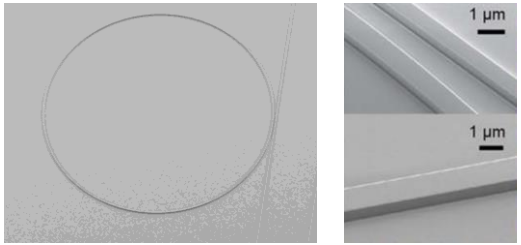
Thin-film LN

- Commercially available thin-film wafers
- Developed ridge waveguide fabrication process



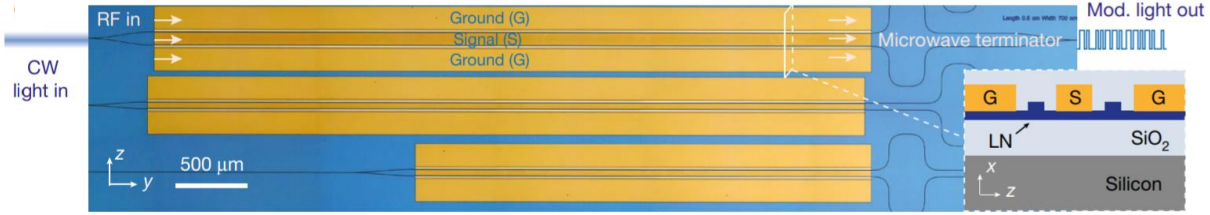
Dispersion engineering – powerful tool for nonlinear optics!

Low-loss waveguides



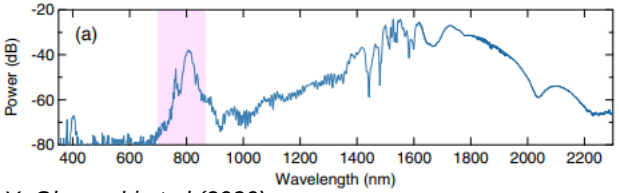
M. Zhang et al. (2017)

Electro-optic modulators



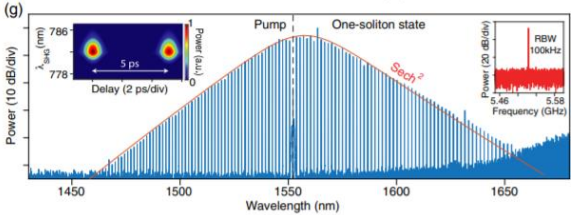
C. Wang et al (2018)

Supercontinuum generation

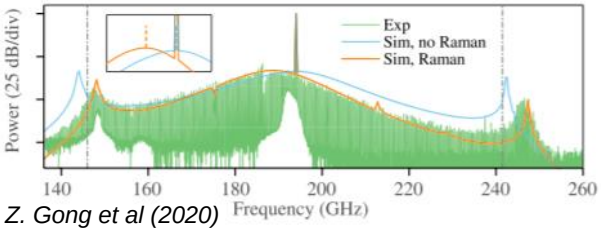


Y. Okawachi et al (2020)

Kerr frequency combs

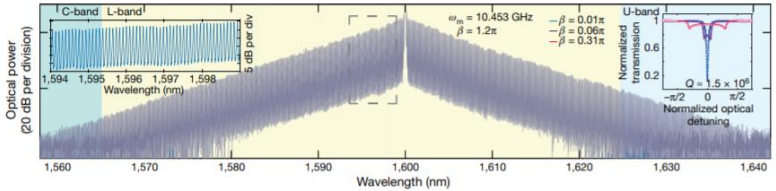


Y. He et al (2019)

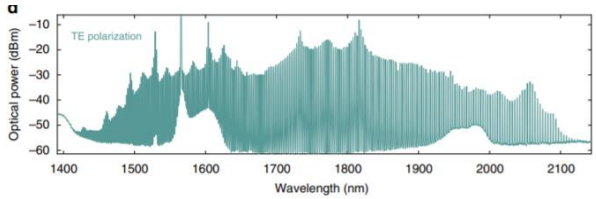


Z. Gong et al (2020)

Electro-optic frequency combs



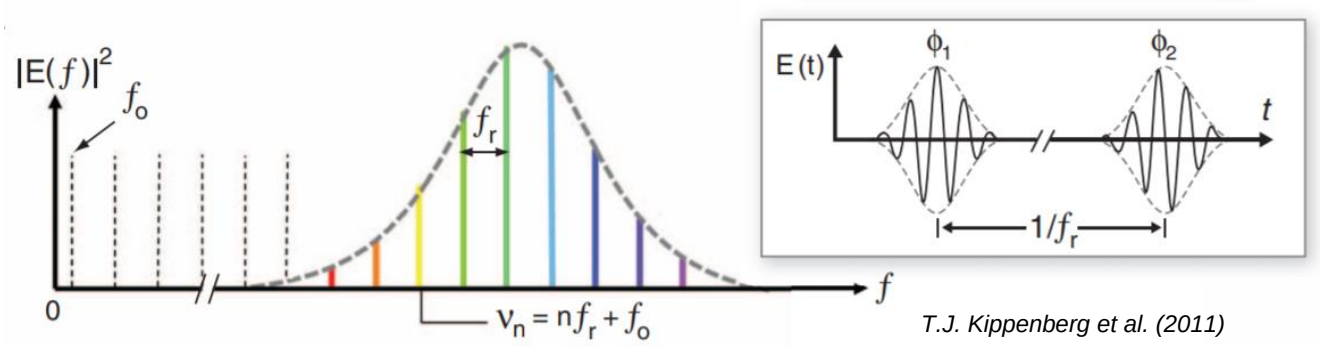
M. Zhang et al (2019)



C. Wang et al (2019)

…and more!

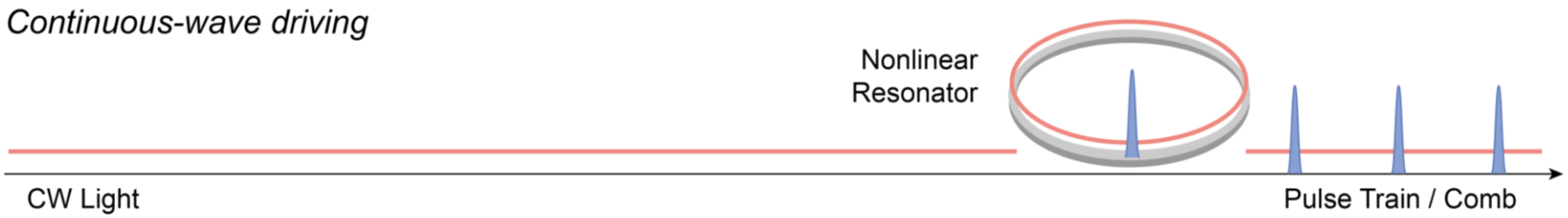
Optical frequency combs



T.J. Kippenberg et al. (2011)

- Compact
- Low power consumption

Frequency comb generation

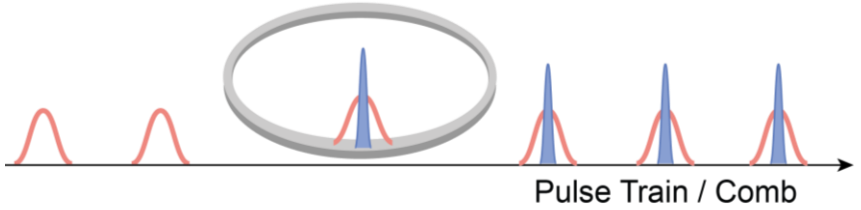


- Generation of octave spanning soliton combs at 100's GHz-THz repetition rates
- Low conversion efficiency (~1%)

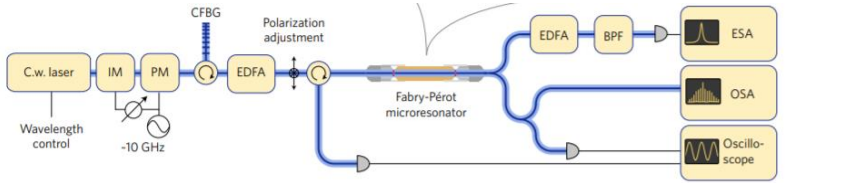
Q. Li et al. (2017)
M.H.P. Pfeiffer et al (2017)
M. Karpov et al (2018)

Frequency comb generation

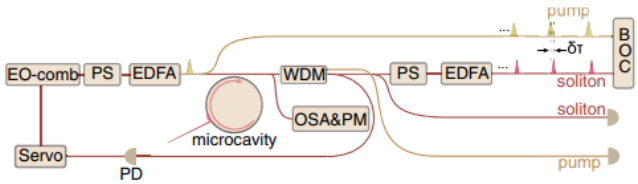
Pulse generation and driving

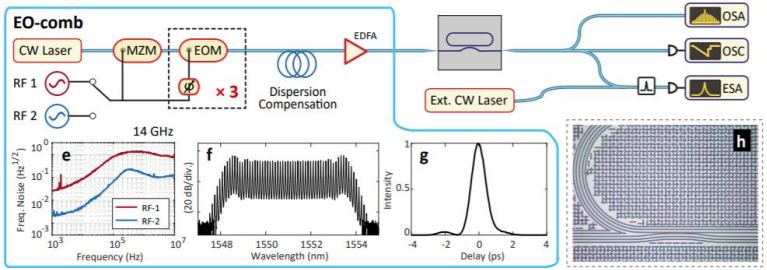


- Higher conversion efficiency (lower average power)



E. Obrzud et al. (2017)



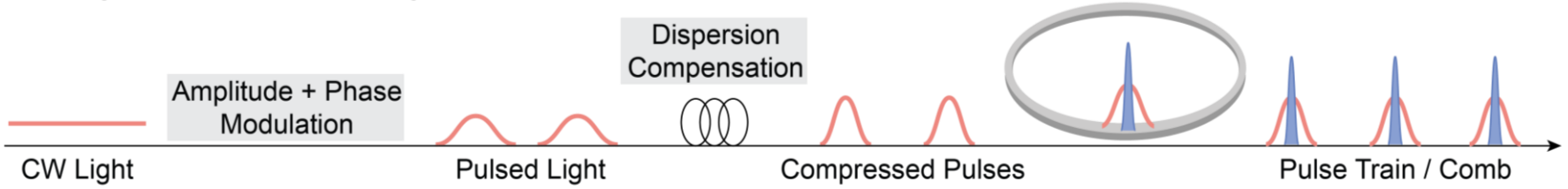


M. Anderson et al. (2020)

J. Li et al. (2022)

Frequency comb generation

Pulse generation and driving



- Higher conversion efficiency (lower average power)

Can we do it all on chip?

Yes, with thin-film lithium niobate!

- Pulse generation
- Dispersion management
- Frequency comb generation

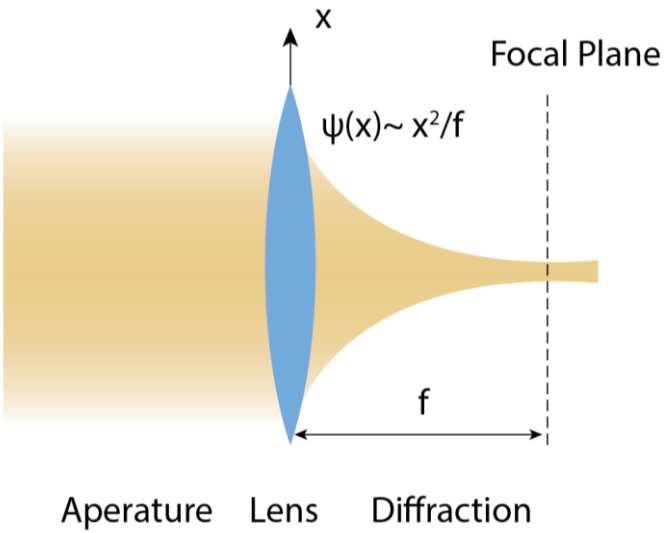
Overview

1. Ultrashort pulse source
2. On-chip dispersion management
3. Nonlinear broadening on thin-film LN

Overview

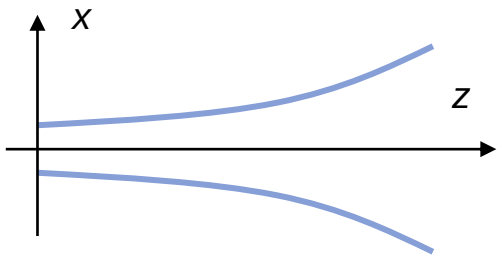
1. **Ultrashort pulse source**
2. On-chip dispersion management
3. Nonlinear broadening on thin-film LN

Time lens concept



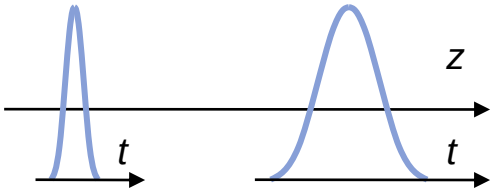
Spatial Domain (Diffraction)

$$\frac{\partial A(x)}{\partial z} = \frac{-i}{2k}\left[\frac{\partial^2 A(x)}{\partial x^2}\right]$$

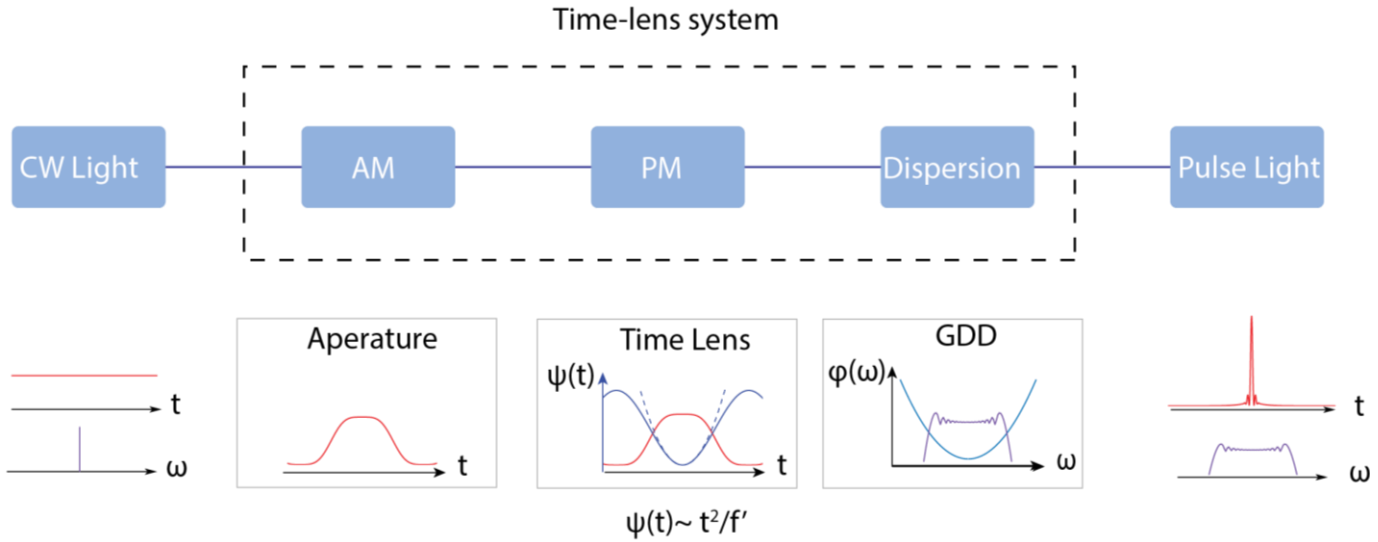


Temporal Domain (Dispersion)

$$\frac{\partial A(t)}{\partial z} = \frac{i\beta_2}{2}\left[\frac{\partial^2 A(t)}{\partial t^2}\right]$$



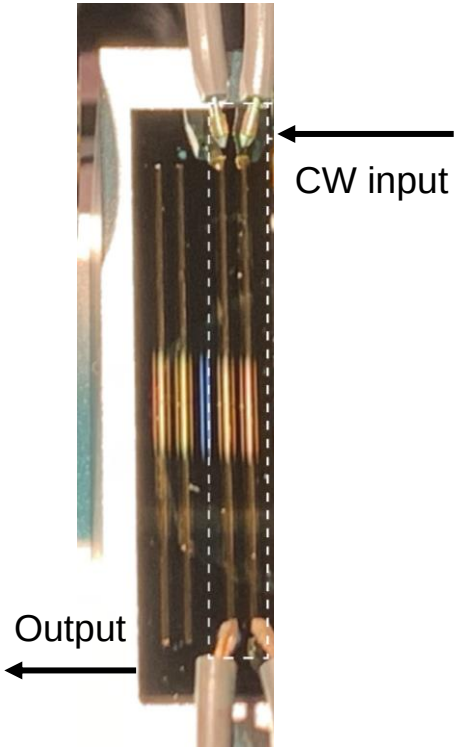
Pulse generation through electro-optic time lens!

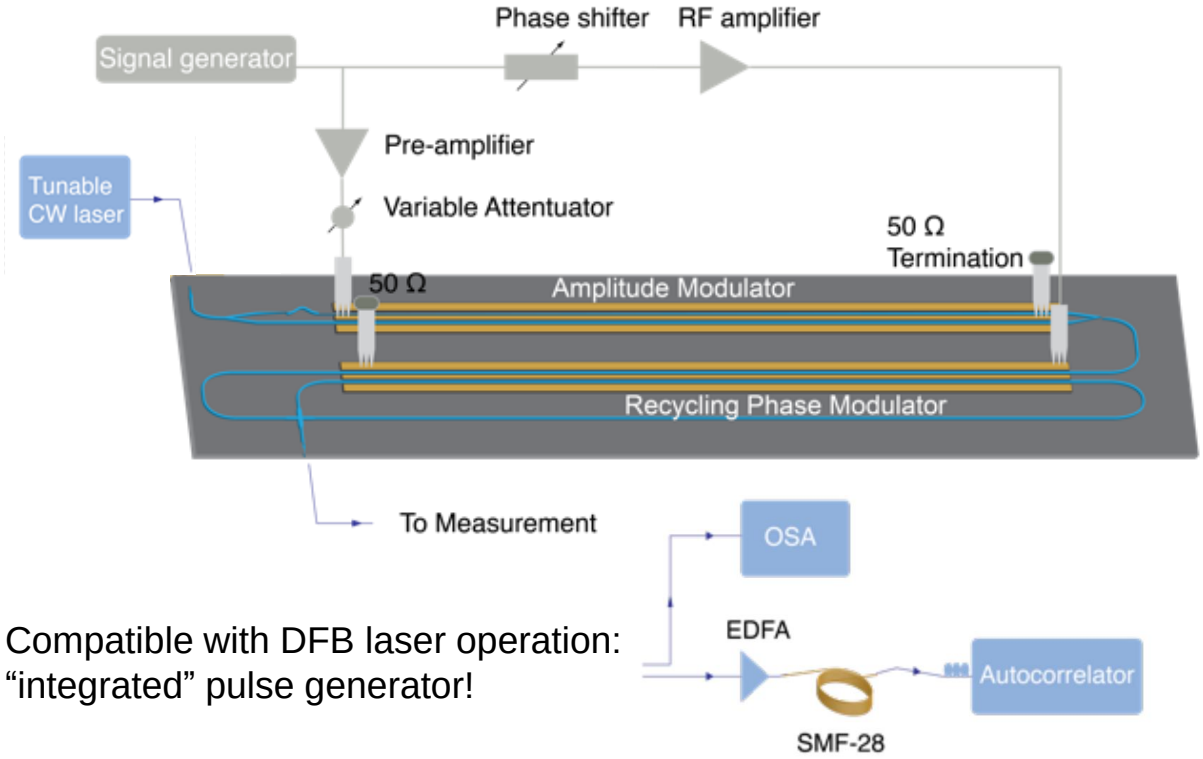


- Amplitude modulator ⟶ numerical aperture
- Phase modulator ⟶ temporal lens
- Dispersion ⟶ propagation length = focal length

M. Yu et al, under review

LN chip and measurement





Compatible with DFB laser operation:
“integrated” pulse generator!

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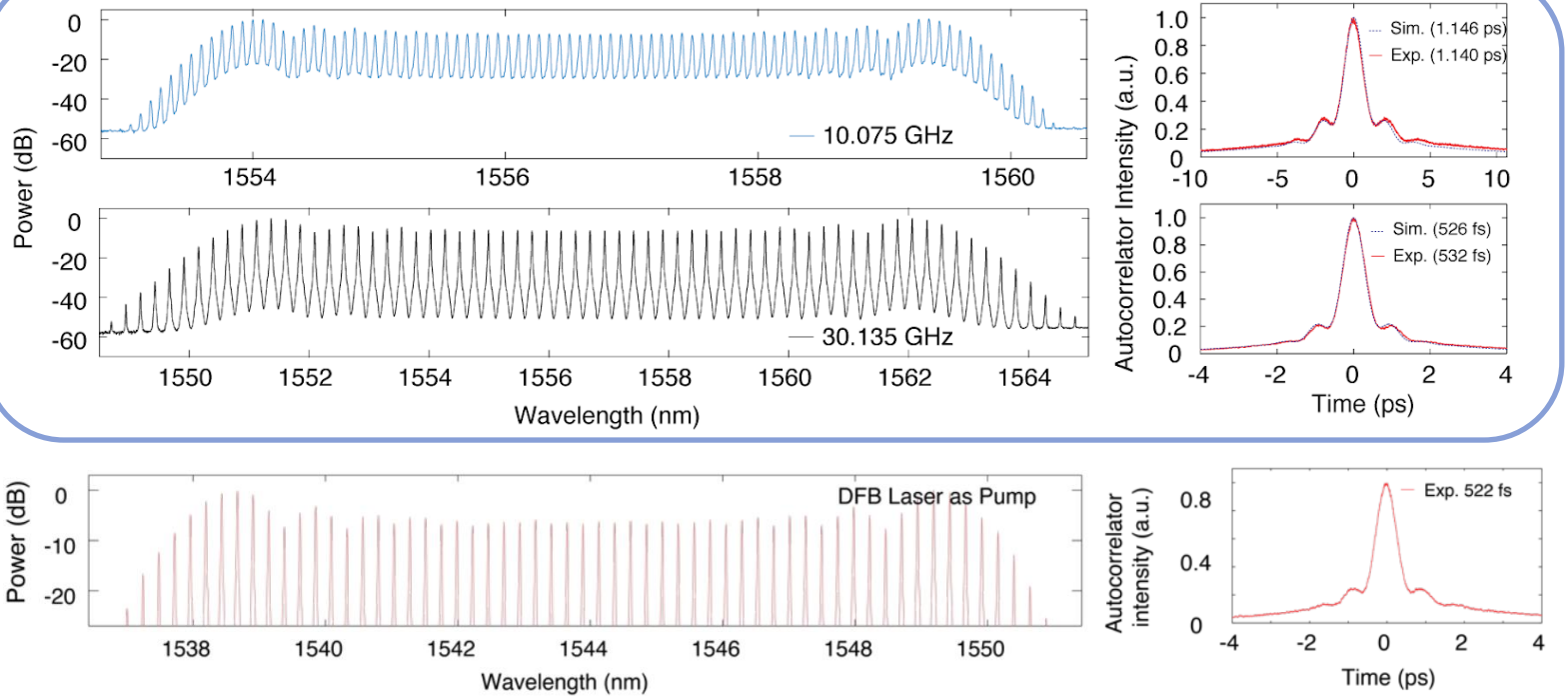
Measurement results



On-chip femtosecond pulse source!

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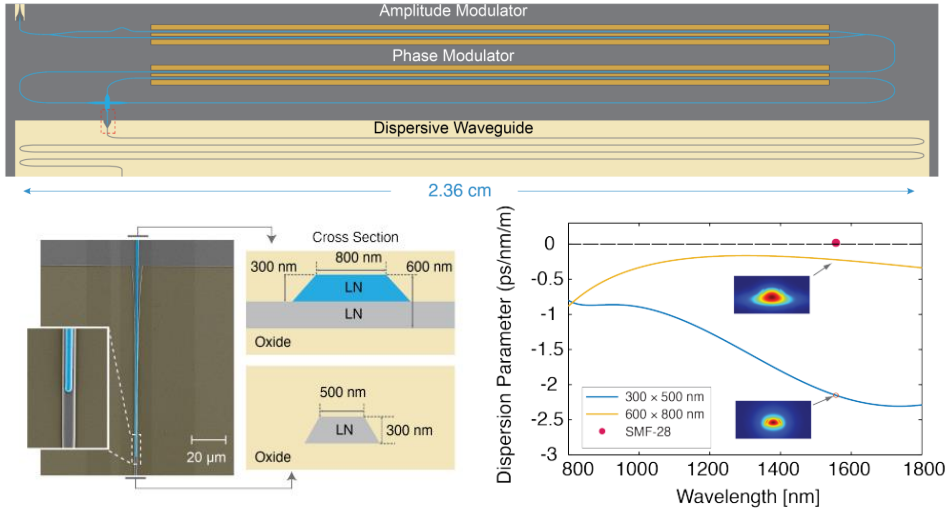
Overview

1. Ultrashort pulse source
2. **On-chip dispersion management**
3. Nonlinear broadening on thin-film LN

On-chip dispersion management

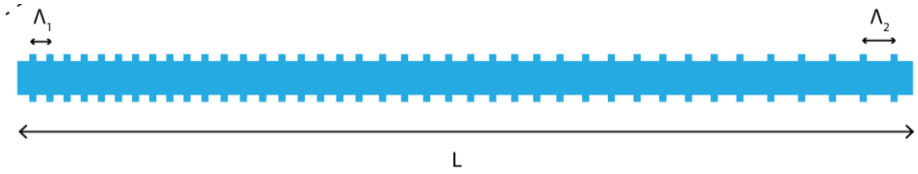
- Move pulse compression on-chip

Dispersive Waveguide



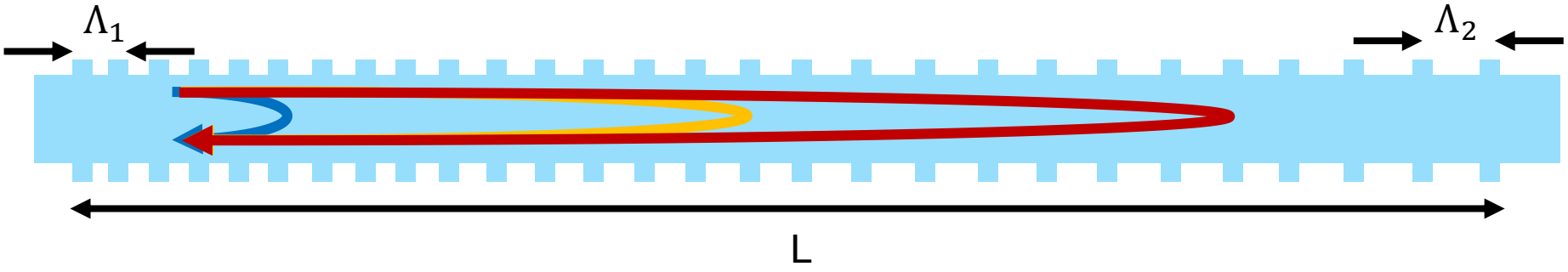
59 m SMF ⟶ 0.49 m dispersive waveguide

Chirped Bragg grating

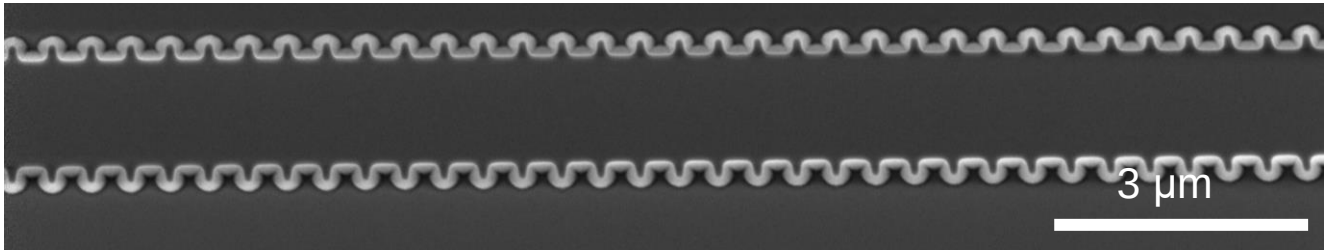


L = 2.5 mm ⟶ Footprint reduced even further!!!

Chirped Grating: Concept

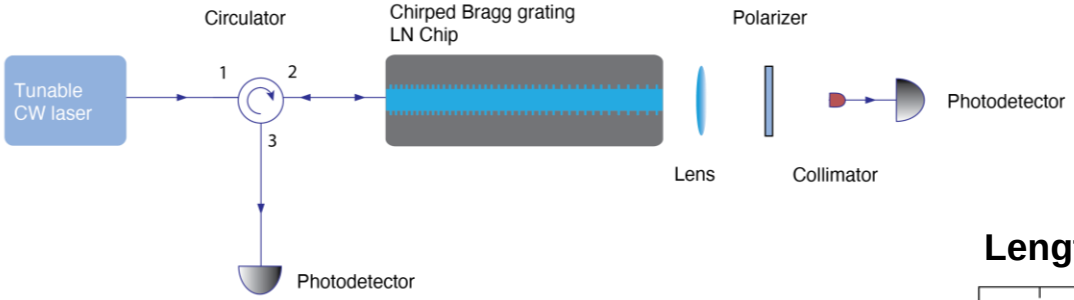


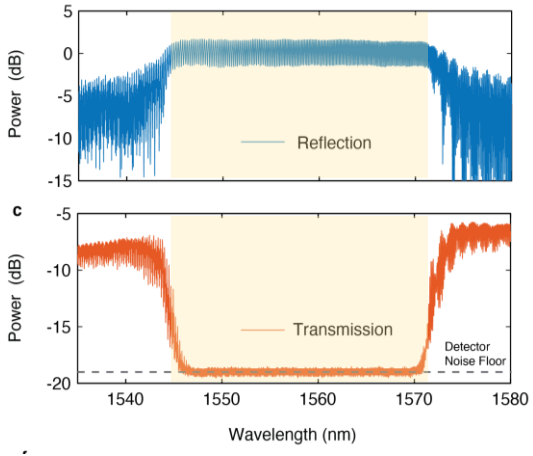
Spectrally-dependent reflector acts as an integrated dispersive delay line!



- Λ_1 = 406.5 nm
- Λ_2 = 414.5nm

Device characterization

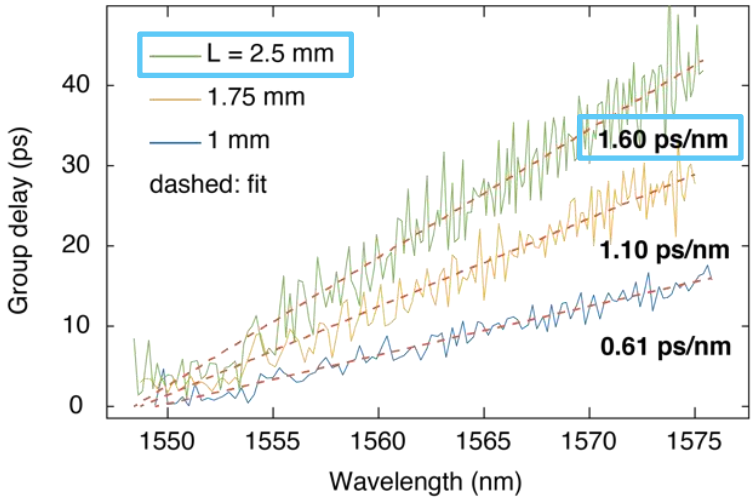




Reflectivity
> 99.5%

Propagation loss
0.3 dB/cm

Length of grating tunes dispersion



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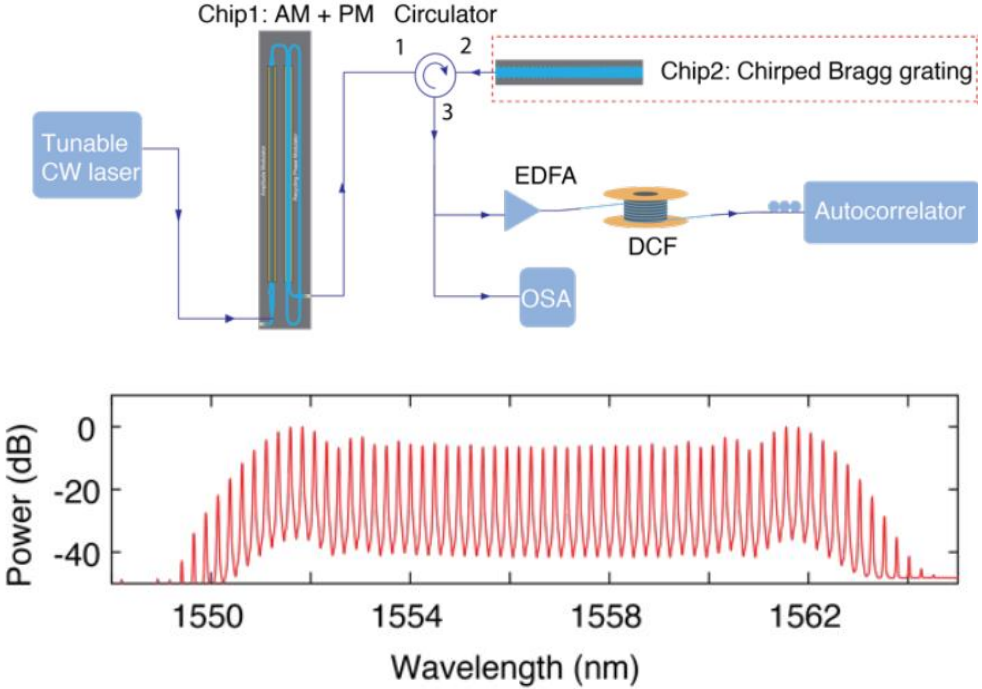
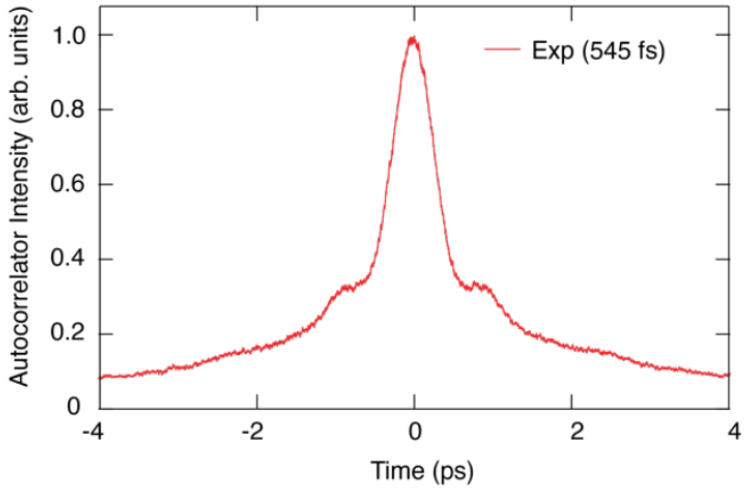
Proof of principle measurement



Comb spectrum unaffected by grating

Near-optimal pulse compression!



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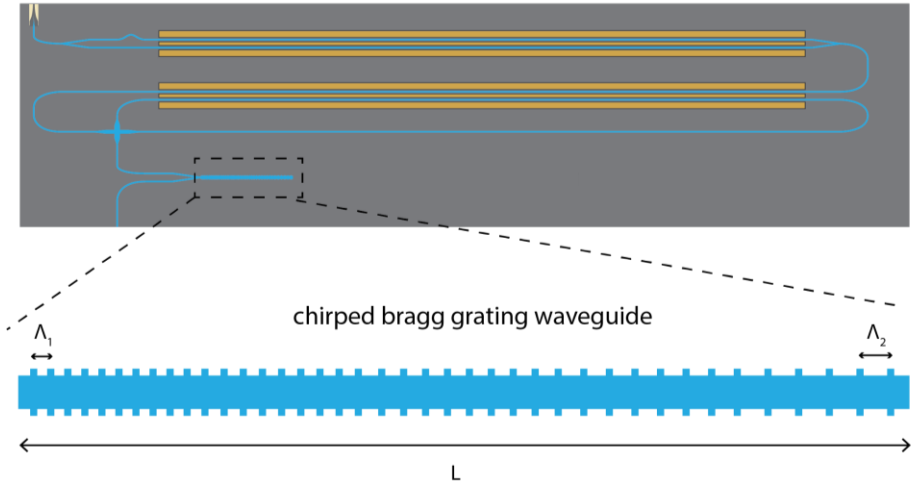
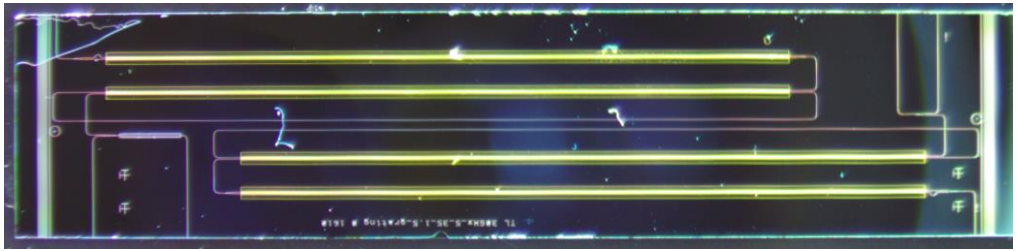
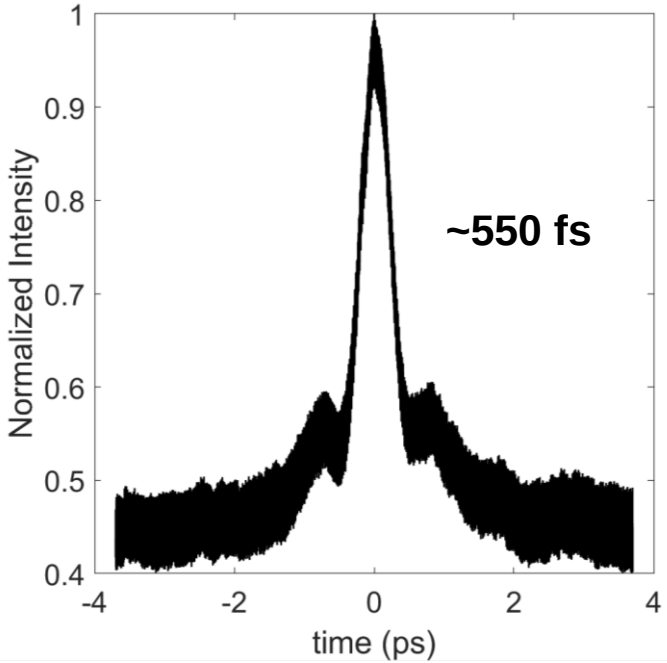
Integrated device!







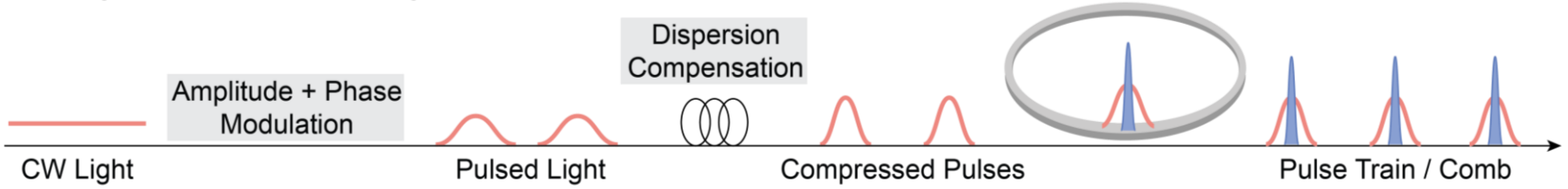
Footprint reduced by **~34,000** when compared to SMF!

Overview

1. Ultrashort pulse source
2. On-chip dispersion management
3. **Nonlinear broadening on thin-film LN**

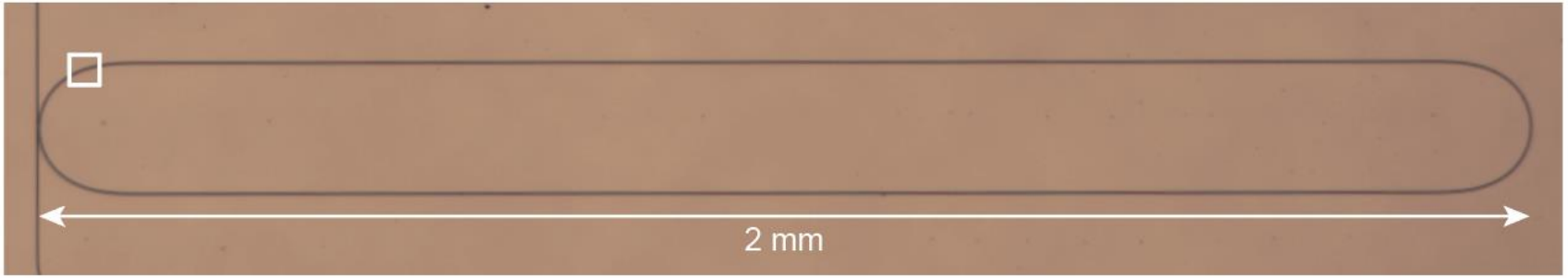
Nonlinear broadening

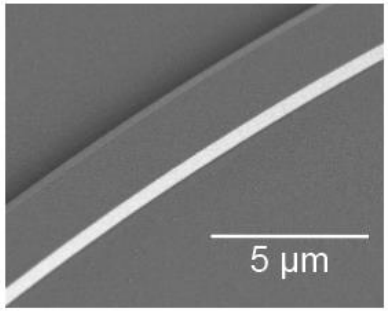
Pulse generation and driving

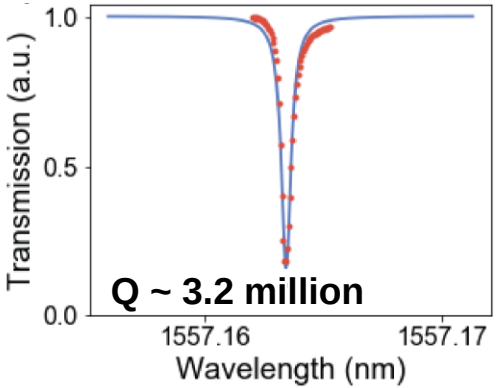


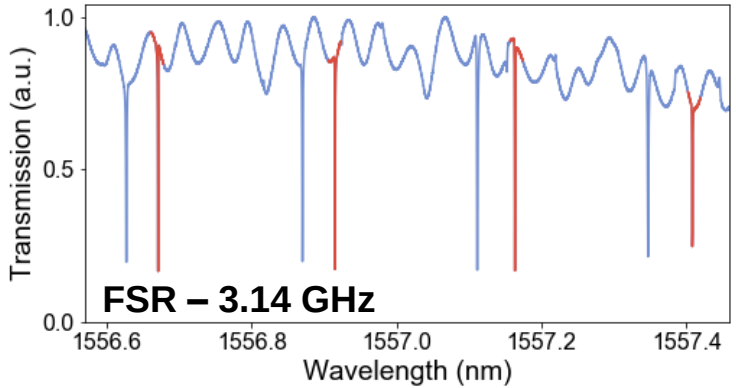
- Pulse generation — **EO modulators** ✓
- Dispersion management — **chirped Bragg grating** ✓
- Frequency comb generation — **high-*Q* microresonator**

Nonlinear resonator



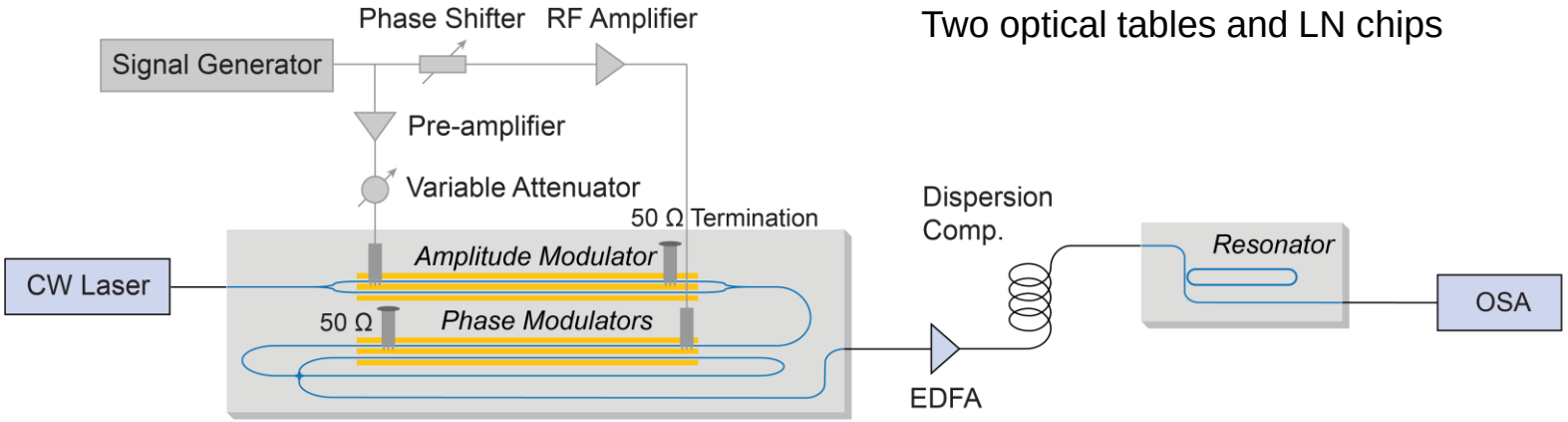




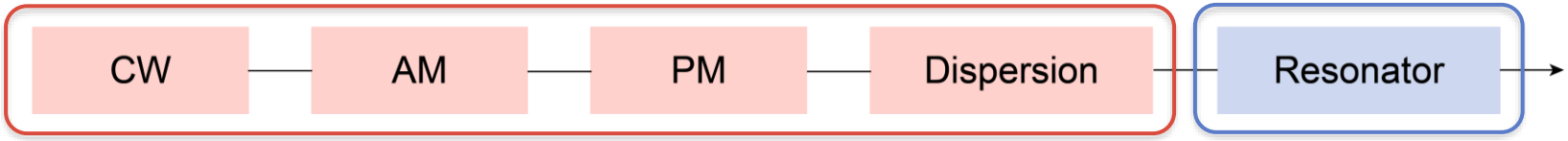


R. Cheng et al, in prep

Experimental setup



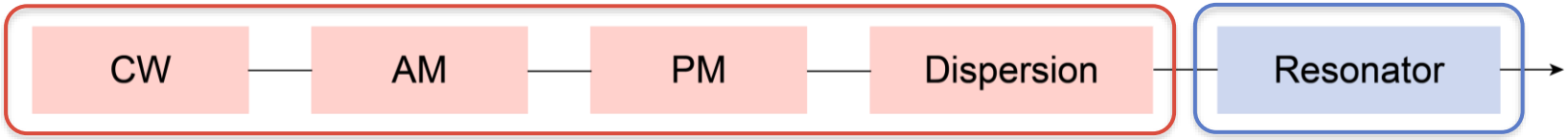
Two optical tables and LN chips



Ultra-short pulse source / electro-optic time lens system

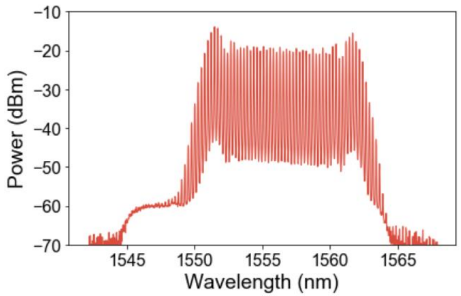
Broadening

Experimental setup

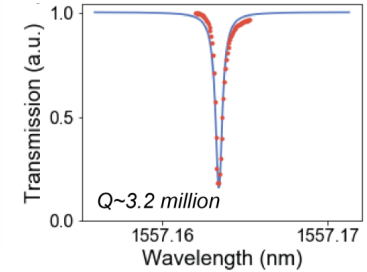


Ultra-short pulse source / electro-optic time lens system

Broadening



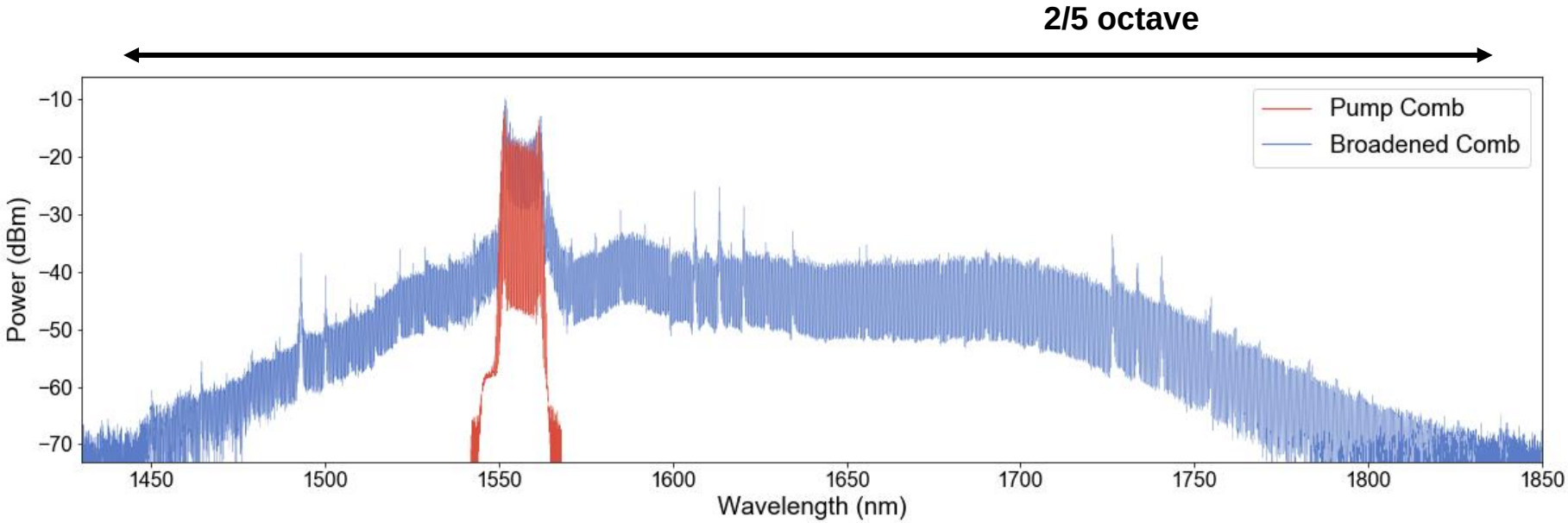
- 30.14 GHz repetition rate
- 530 fs pulse duration



- 12.5 mW average on-chip power
- 0.8 W peak power
- 0.45 pJ pulse energy

R. Cheng et al, in prep

Results



- 0.45 pJ pulse energy
- ~400 nm bandwidth at 30.1 GHz repetition rate

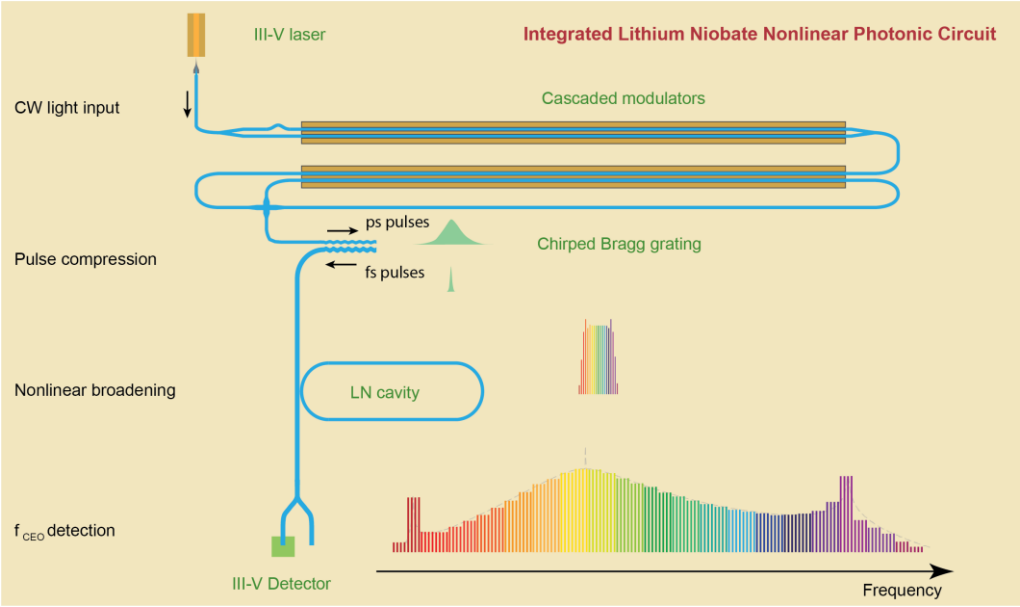
Over 1500 comb lines

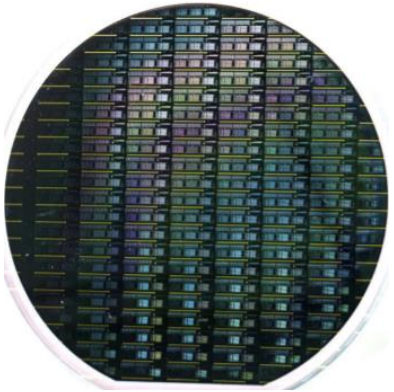
~6% conversion efficiency

R.Cheng et al, in prep

Conclusions and outlook

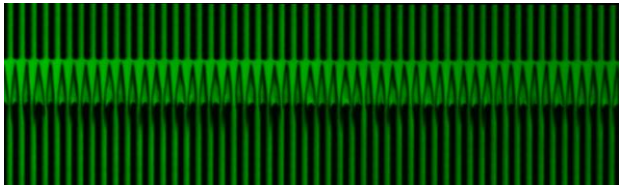
- Thin-film LN is an excellent material platform for nonlinear optics
- Demonstrated **on-chip** ***pulse generation***, ***pulse compression***, and ***pulse broadening*** on thin-film LN





K. Luke et al (2019)

C.J. Xin



Acknowledgements

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HyperLight

Christian Reimer

Lingyan He

Kevin Luke

Mian Zhang

And the rest of the Lončar group!