# Generation of few-cycle terahertz pulses in domain-engineered lithium niobate crystals

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1. *Introduction.*
2. *THz generation by OR of fs-laser pulses in LN and PPLN crystals.*
3. *Nearly single-cycle THz Generation in APPLN.*
4. *THz waveform and spectra in APPLN.*
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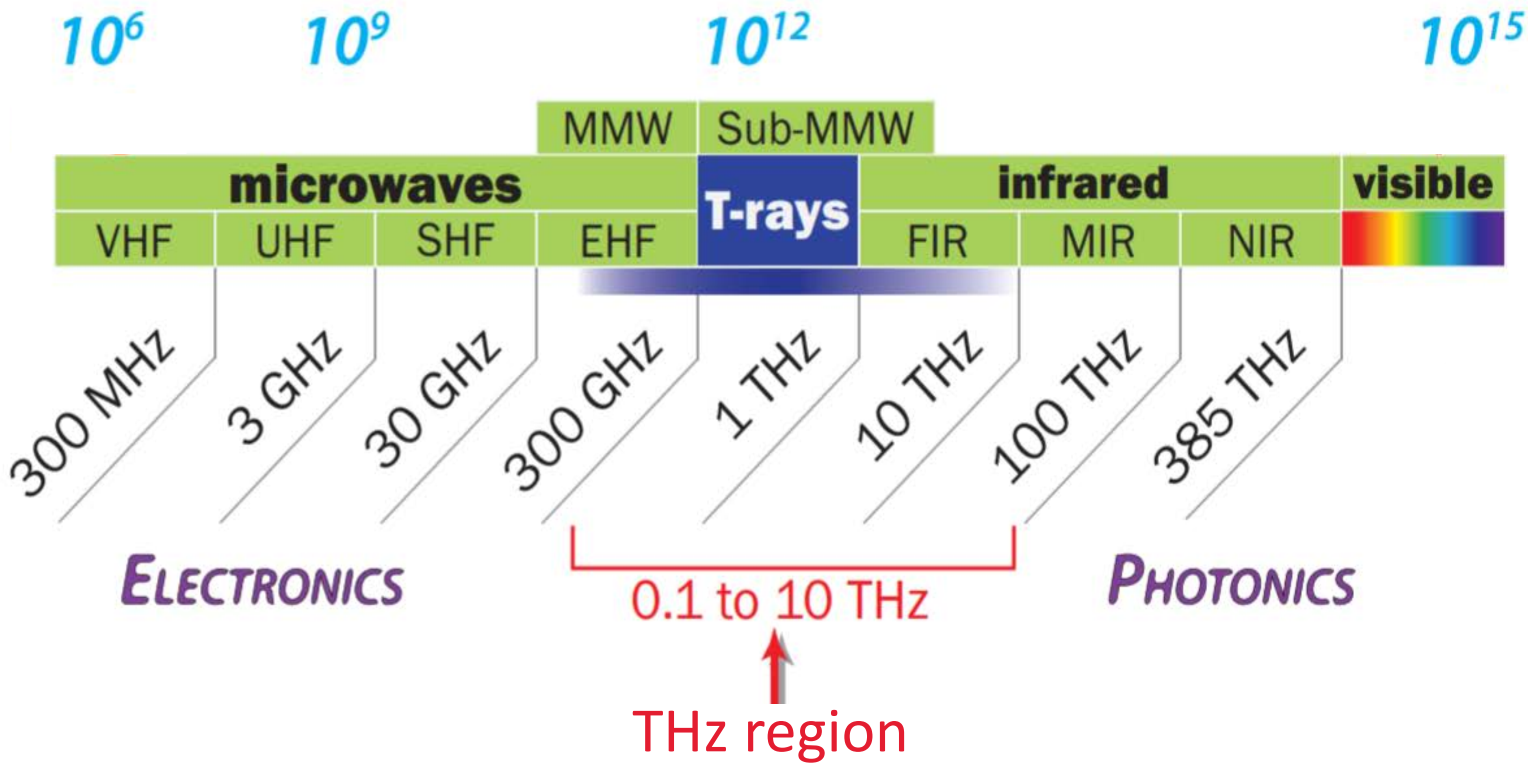
# The electromagnetic spectrum



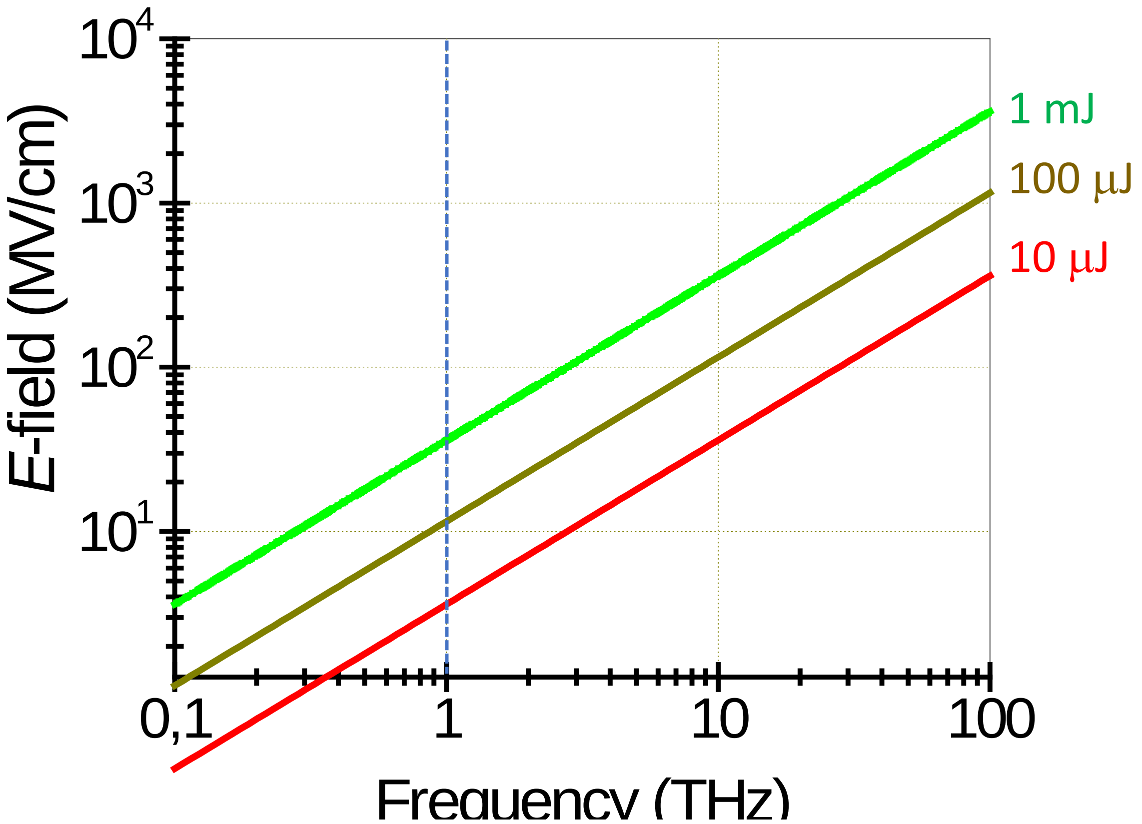

1 THz $\Rightarrow$ 1 ps @ 300 $\mu$m @ 4.1 meV @ 47.6 K

# Applications & Properties

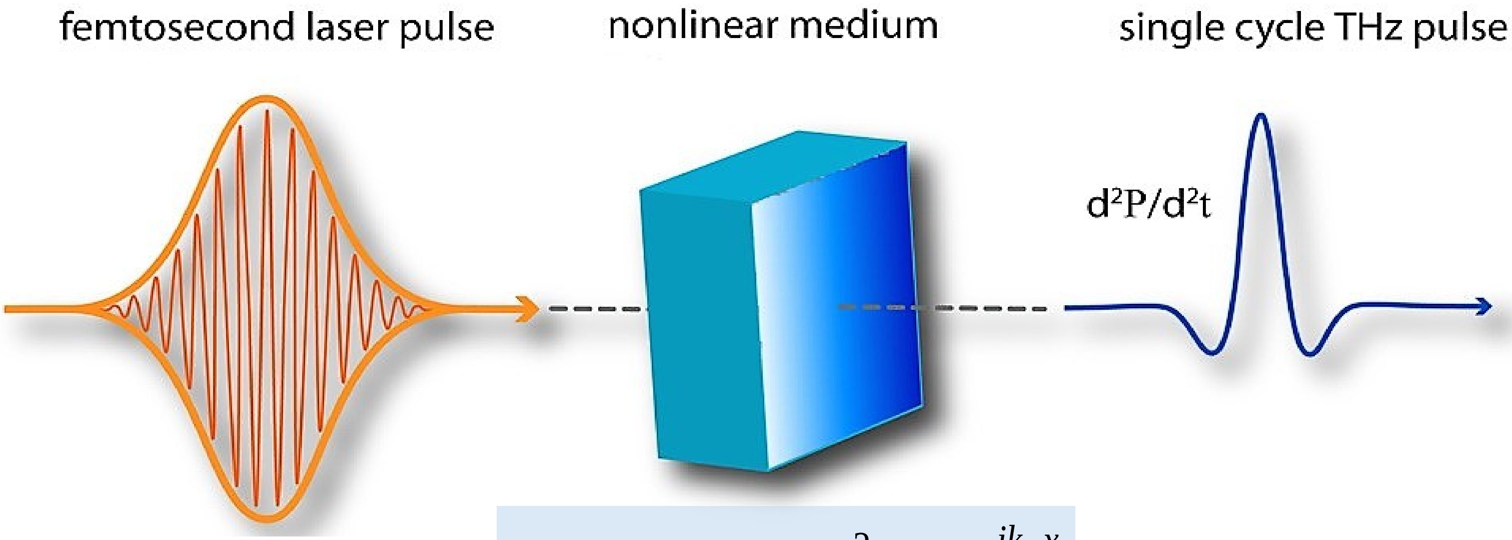
- ***Spectroscopy and material science***: unique spectral signatures for large bio-molecules and chemicals.
- ***Sensing and Imaging***: non-ionizing photon energy, penetration capability through optically opaque materials. In contrast to microwave, the shorter wavelength improves the resolution in imaging applications.
- ***Wireless communication***: extremely wide THz-wave bandwidth supporting peak data rates of 1 Tbit/s.
- **Charged particle acceleration:** availability of high electrical field $E$ > 10 MV/cm at long wavelength, which compares well with typical sizes of particle bunches.

# E-field strength in focus vs frequency

*Field strength in focus with f-number* = 1



# Optical rectification




$$P_{NL}(t) = \chi_{NL} E_m^2(t) e^{-ik_g x}$$

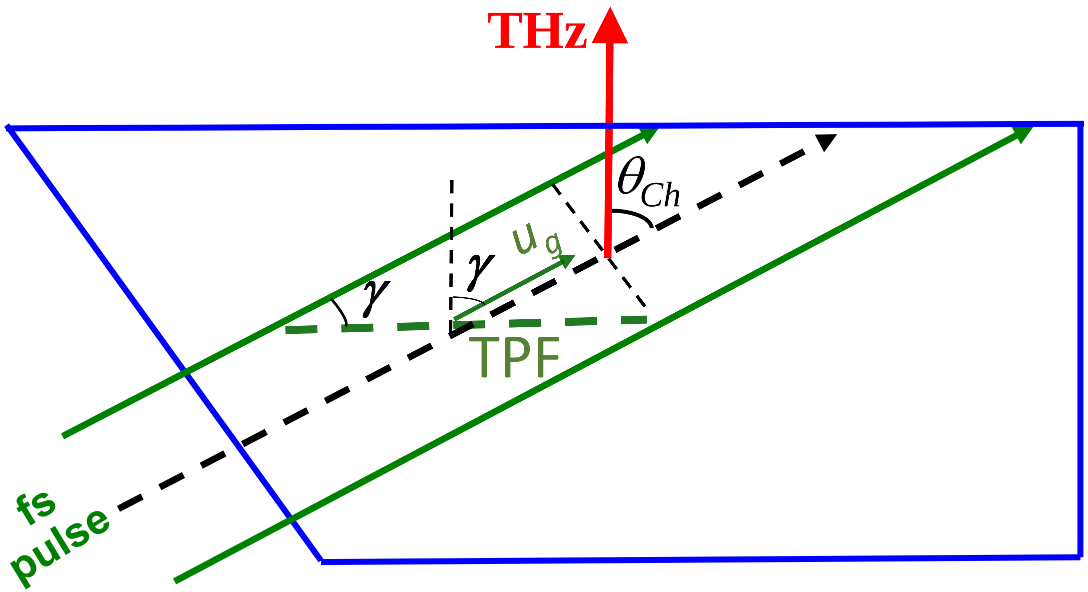
$$E_{opt}(t) e^{i(\omega_0 t - k_0 x)}$$

$$\propto \dot{P}_{NL}(t) e^{-ik_{THz} x}$$

$$\Delta \mathrm{v} = \mathrm{v}_g - \mathrm{v}_{THz} = c\left(n_g^{-1} - n_{THz}^{-1}\right)$$

for $LiNbO_3$: $n_g \approx 2.3$, $n_{THz} \approx 5.2$

# Tilted-pulse-front pumping



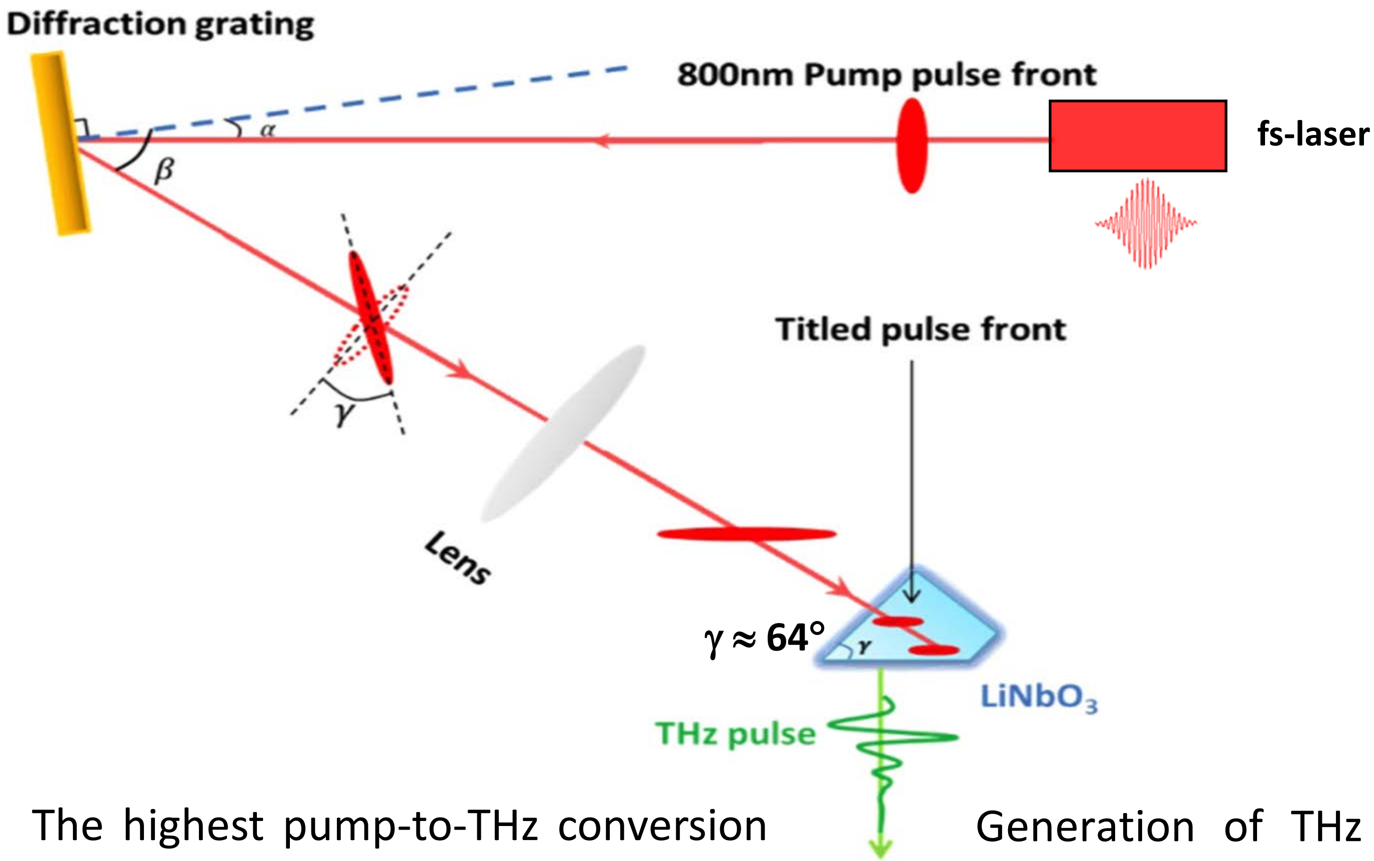

*J. Hebling et al. Opt. Lett.* ***10****, 1161, (2002).*

<u>For phase matching:</u>

$$(c/n_g)\cos\gamma = (c/n_{THz}) \Rightarrow \cos\gamma = n_g/n_{THz} = \cos\theta_{Ch}.$$

TPF angle has to be $\gamma = 64°$ in $LiNbO_3$.

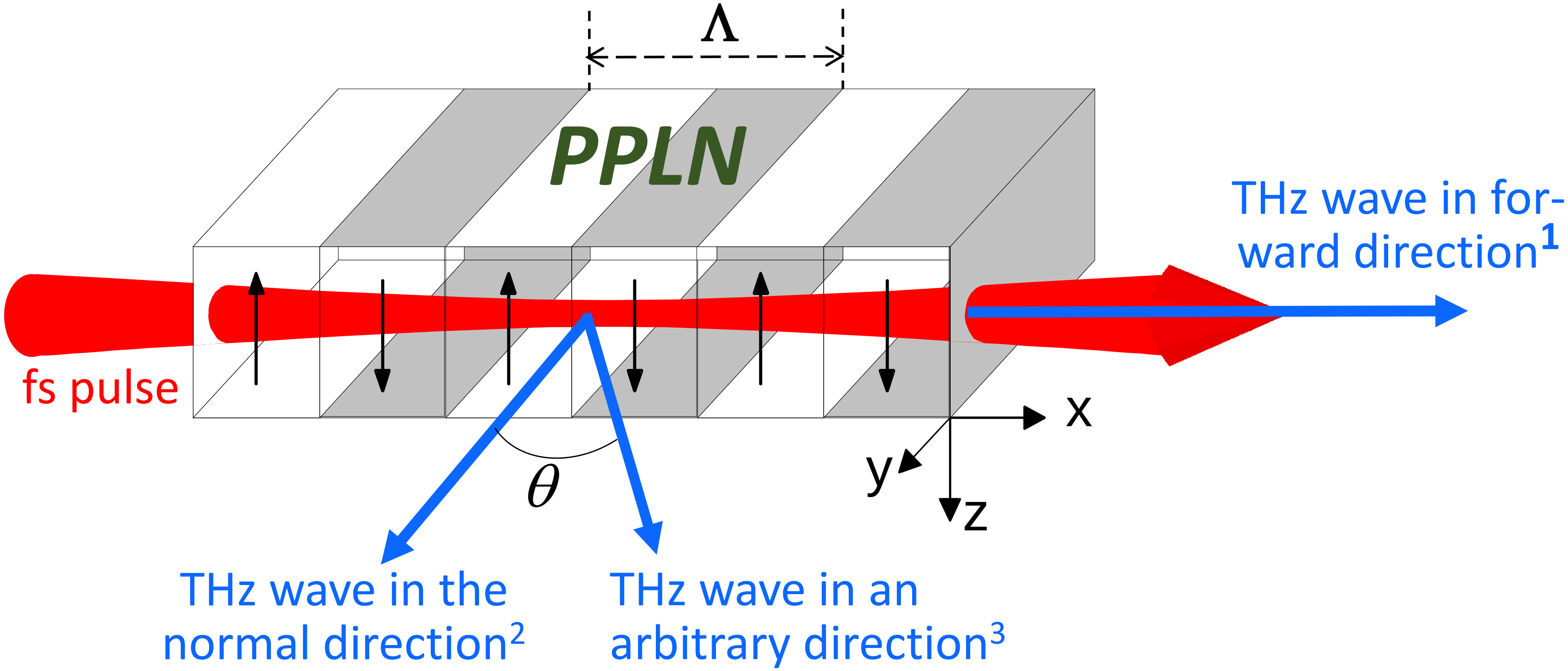
# Scheme of OR with TPF excitation




The highest pump-to-THz conversion efficiency $\eta$ = 3.8% in cryogenically cooled $LiNbO_3$ was reported by *S. Huang* et al. Opt. Lett. **38,** 796 (2013).

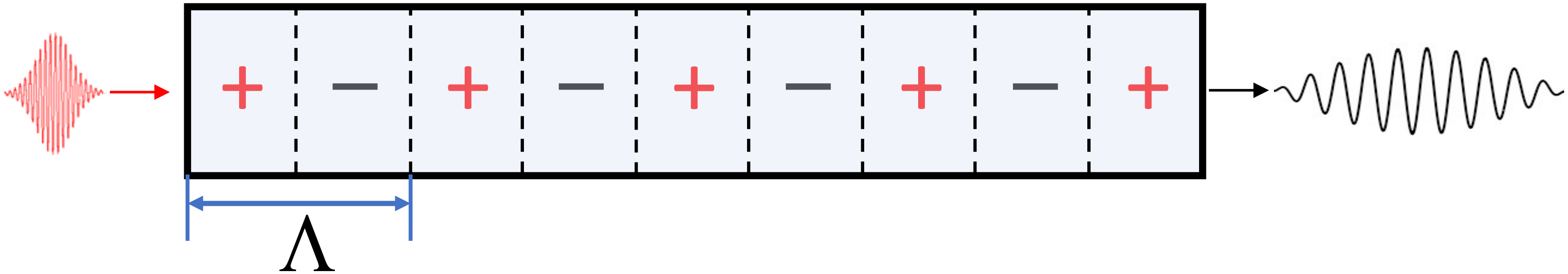
Generation of THz pulse with energy 0.4 mJ in $LiNbO_3$ crystal was reported by *J. Fülöp,* et al. Opt. Exp. **22**, 20155, (2014).

# THz generation in various directions




1. Y. S. Lee, T. Meade, T. B. Norris, A. Galvanauskas, APL **76,** 2505 (2000).
2. C. Weiss, Y. Avetisyan, R. Beigang, 1st THz Workshop, 17-19 Sept. 2000, Denmark.
3. C. Weiss, G. Torosyan, Y. Avetisyan, R. Beigang, Opt. Lett. **26**, 563 (2001).

# Multi-cycle THz pulses in PPLN




$$\frac{\omega_{THz} n_g}{c}\cos\theta + \frac{2\pi}{\Lambda} = \frac{\omega_{THz} n_{THz}}{c}$$

$$\omega_{THz} = \left| \frac{2\pi c}{\Lambda(n_{THz}\cos\theta - n_g)} \right|$$

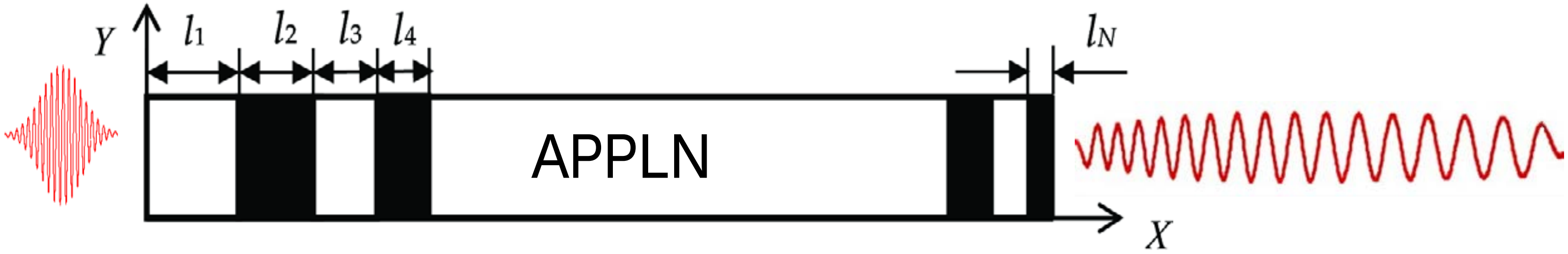
# Motivation

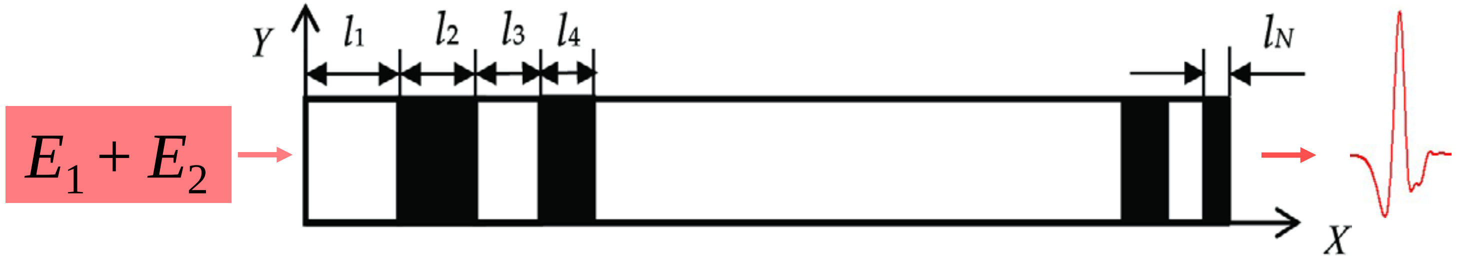
1. The necessity of THz pulses with controllable number of the THz field oscillations from single- to multi-cycles.
2. Availability of the ps- and fs-laser sources with high-energy of the laser pulses.
3. Recent progress in the fields of PPLN crystal fabrication and shaping of the laser pulses. The large area PPLN crystals are commercially available, and even a crystal with dimensions 10 x 15 $mm^2$ was recently used for THz generation with energy of pulse about 0.4 mJ [4,5].


[4] F. Kärtner, *Proc. High-brightness Sources Congress*, 2018, MW3C.1.

[5] S. Jolly et al. *Nature Comm.* **10**, 2591 (2019).

# Single-cycle THz generation in APPLN



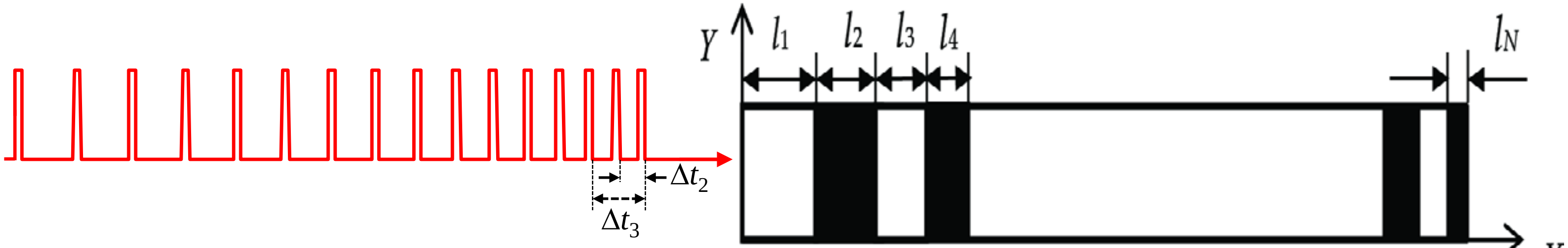




$$E_1 = E_{1m} e^{-(t/\tau)^2} e^{i(\omega_1 t - k_1 x)}$$

$$E_2 = E_{2m} e^{-(t/\tau)^2} e^{ibt^2} e^{i(\omega_2 t - k_2 x)}$$

K. Ravi, F. Kärtner, *Opt. Express* **27**, 6580 (2019)

# APPLN pumped by sequence of pulses



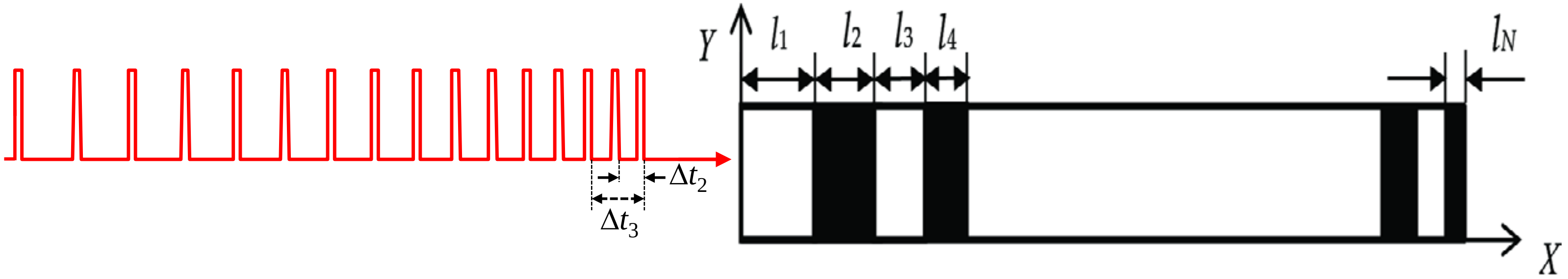

$l_k = [l_1 - (k-1)\cdot\delta]$, $l_1 = 90$ μm, $\delta = 1.6$ μm, and $k = 1, 2, \ldots 32$.

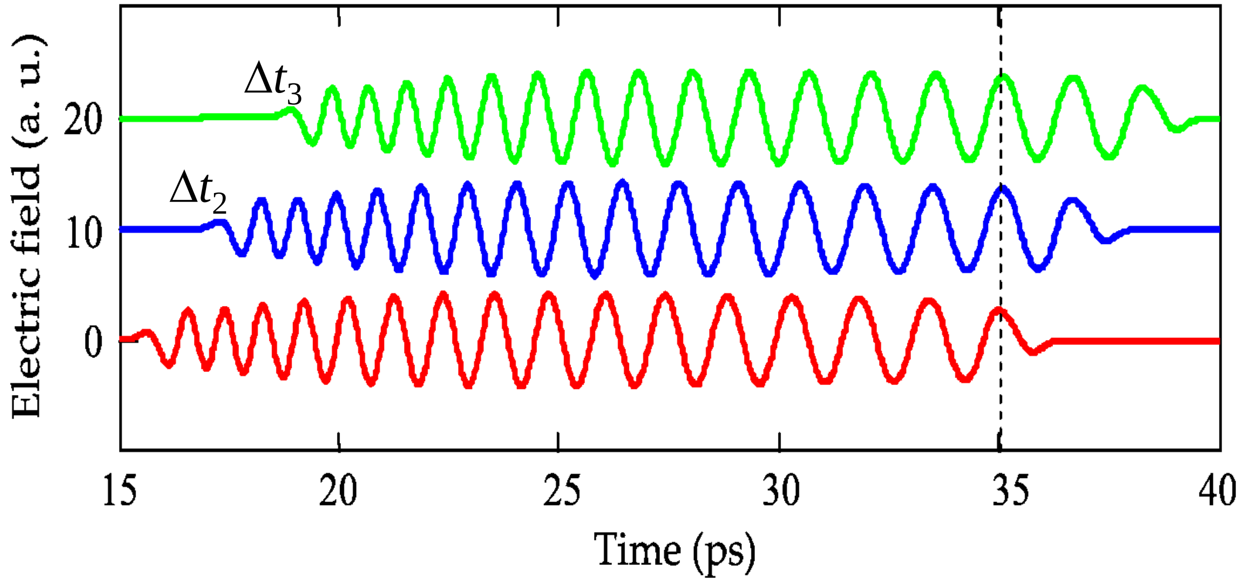
$$E(t_r) = A_0 \sum_{m=1}^{N} (-1)^{m+1} \left[ \dot{I}(t+\tau_m) - \dot{I}(t+\tau_{m+1}) \right],$$

where $t_r = t - t_0$, $t_0 = (L + R)n_{THz}/c$,

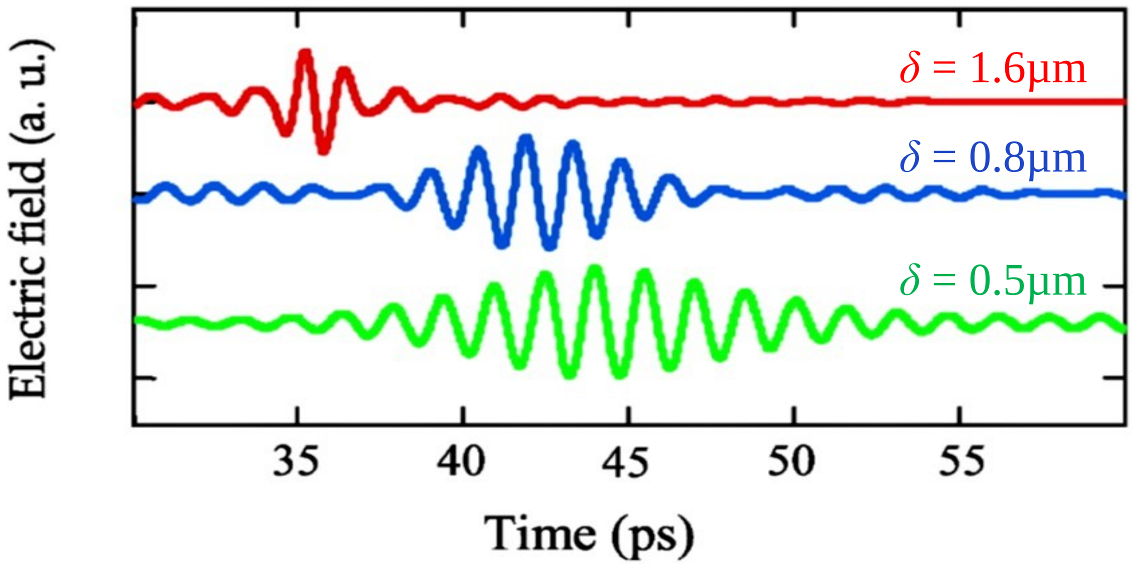
$$\tau_m = \frac{\Delta n}{c} \sum_{k=1}^{m-1} l_k, \; \Delta n = n_{THz} - n_g \, .$$

# Overlapping fields from different domains



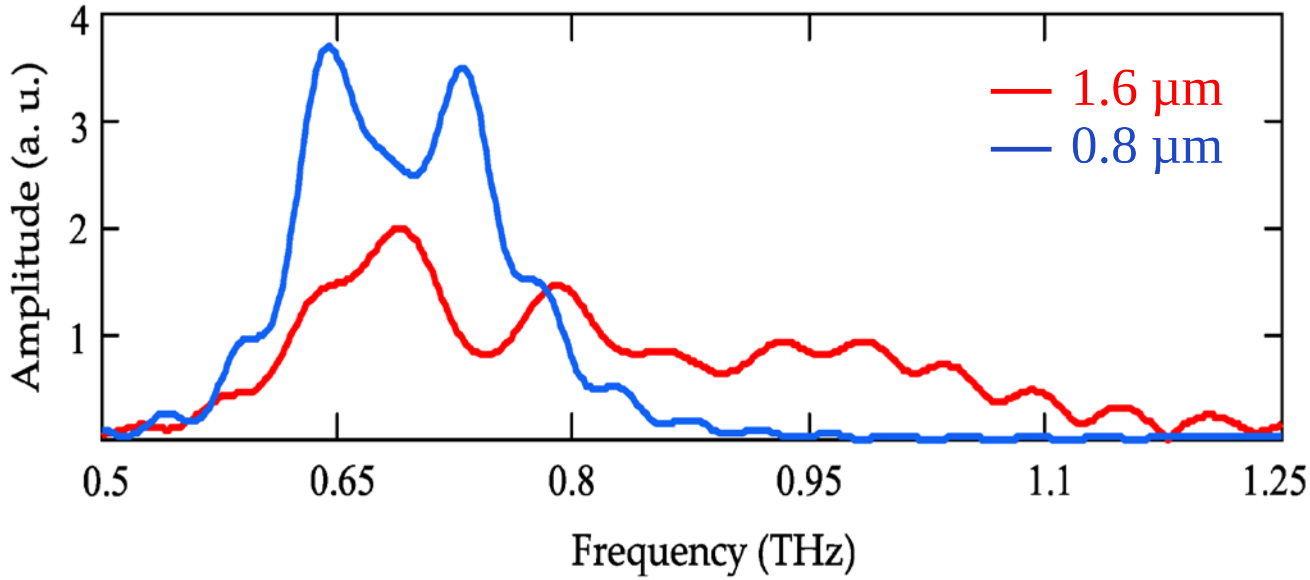



# APPLNs with different chirp rate $\delta$




Control on the number of THz field oscillations, from nearly single- to multi-cycles.

# Spectrum of THz pulses




Spectrum of the multi-cycle THz pulse in APPLN with $\delta$ = 0.8 μm lies in range of 0.6-0.8 THz that is beneficial for THz waveguide based particle acceleration.

# Numerical estimations

For pump intensity of 20 GW/cm$^2$
and beam area of $S$ = 7 mm$^2$

1. Peak THz electric field $E_{max} \approx$ 0.3 MV/cm
2. THz field in focus of lens 15 – 30 MV/cm.
3. Efficiency of pump/THz conversion $\approx$ 0.2%.

# Conclusions

1. A simple theoretical model is developed for nearly single-cycle THz pulse generation in a chirped APPLN crystal.
2. The peak THz electric field strength of 0.3 MV/cm is predicted for 20 GW/cm$^2$ intensities of the separate laser pulses in the sequence.
3. By focusing the THz beam and increasing the pump power, the electric field strength can reach values in the order of a few tens MV/cm.

**Thank for your attention**