Narrowband THz pulse generation in artificial 2-D periodically poled lithium niobate crystal

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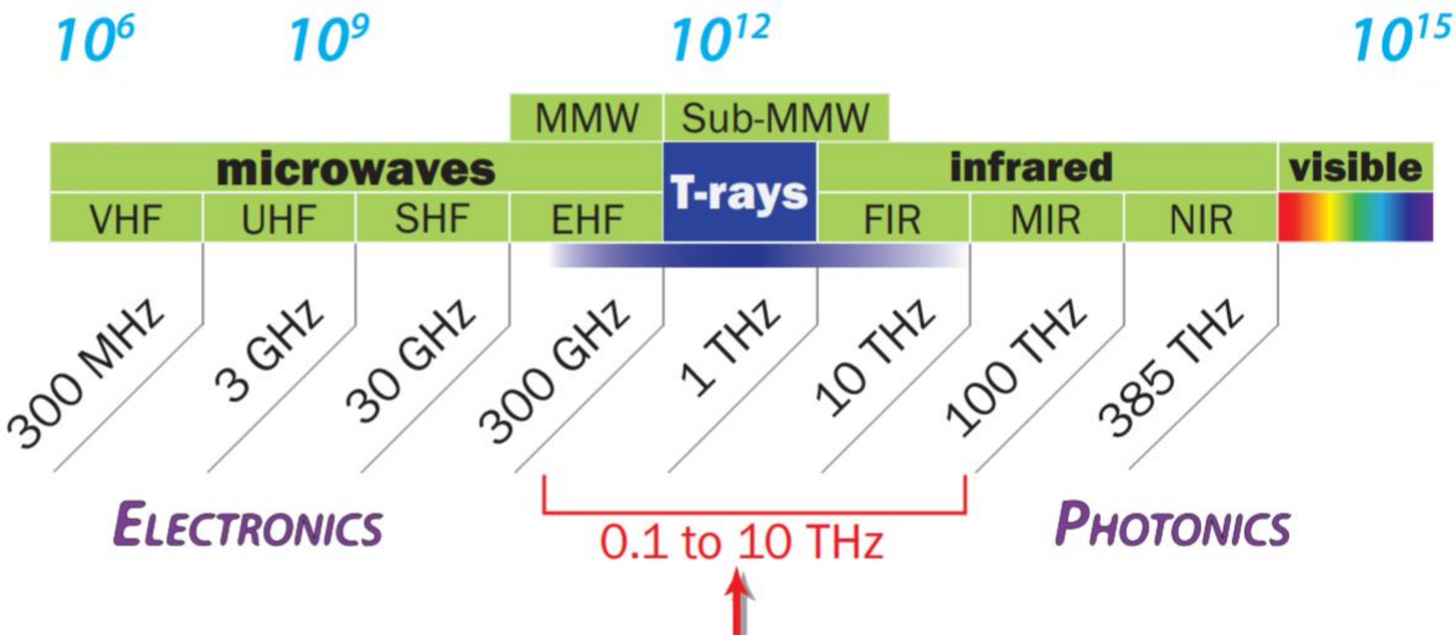
THz region

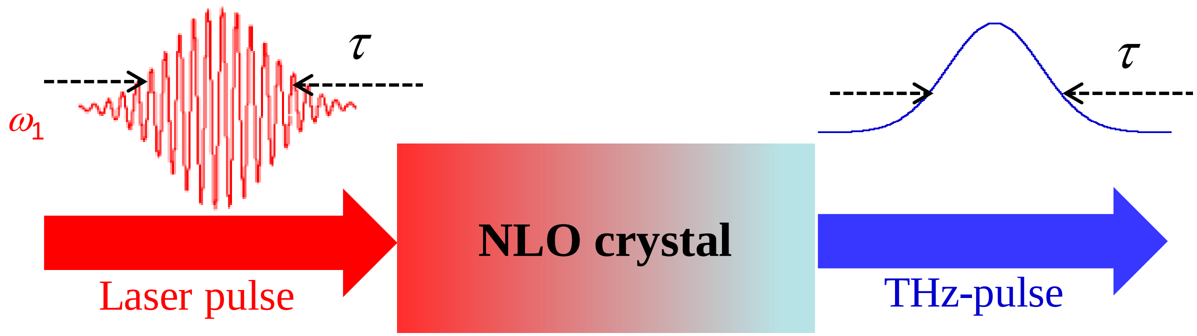


1 THz $\Rightarrow$ 1 ps @ 300 μm @ 4.1 meV

Attractive features of THz waves

- ***Signature***: Rotation and vibrational modes of many molecule lie within the THz spectral range.
- ***Safely***: THz-ray has low photon energy (~10^6 times weaker than a X-ray photon) and will not cause harmful photoionization in the biological tissues.
- ***Transparency and resolution***: Most materials such as plastic, paper, cardboard, textiles and ceramics are transparent to THz radiation. In contrast to microwave, the shorter wavelength improves the resolution in imaging applications.
- ***Wireless communication***: Extremely wide bandwidth (up to several THz) leads to potential speed of several Tbit/s for 5G and future 6G communication standards.
- ***Charged particle acceleration***: Compromise between the large λ and low acceleration gradient of microwave and the small λ but high acceleration gradient of optical radiation.

Optical rectification in NLO crystal



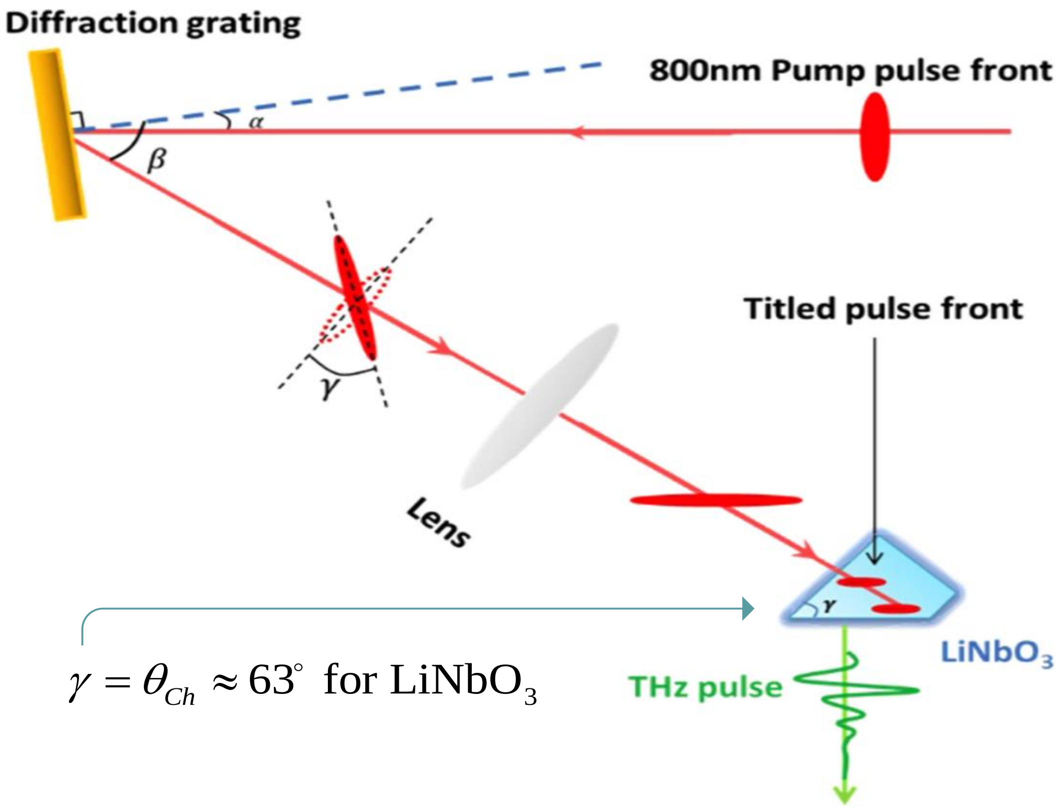
$$\boxed{\vec{k}_{THz} = \vec{k}_g}$$

$k_{THz} = \omega / v_{THz}$

$k_g = \omega / u_g$

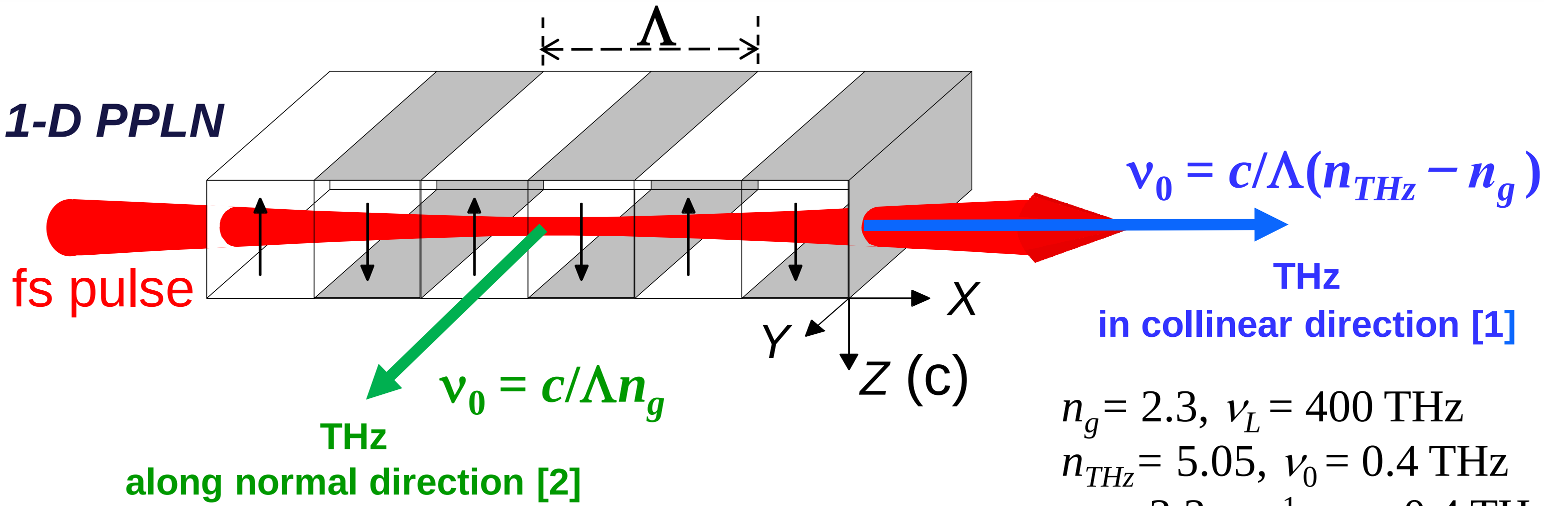
$n_{THz} = n_g$

Tilted pulse-front (TPF) pumping technique

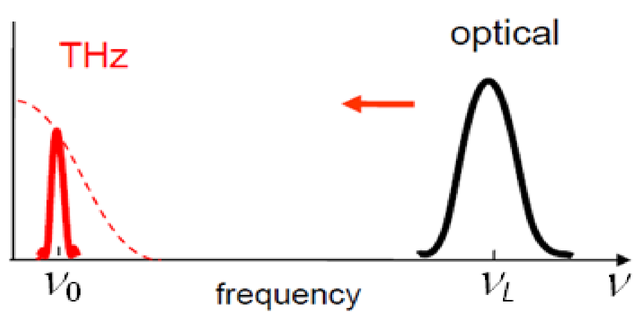


$$\gamma = \theta_{Ch} \approx 63^{\circ} \text{ for LiNbO}_3$$

Narrowband THz generation in 1D-PPLN



$n_g = 2.3,\ \nu_L = 400$ THz
$n_{THz} = 5.05,\ \nu_0 = 0.4$ THz
$\alpha \approx\ 3.3\ \text{cm}^{-1},\ \nu_0 = 0.4$ THz
$\alpha \approx\ 33.6\ \text{cm}^{-1},\ \nu_0 = 1.6$ THz



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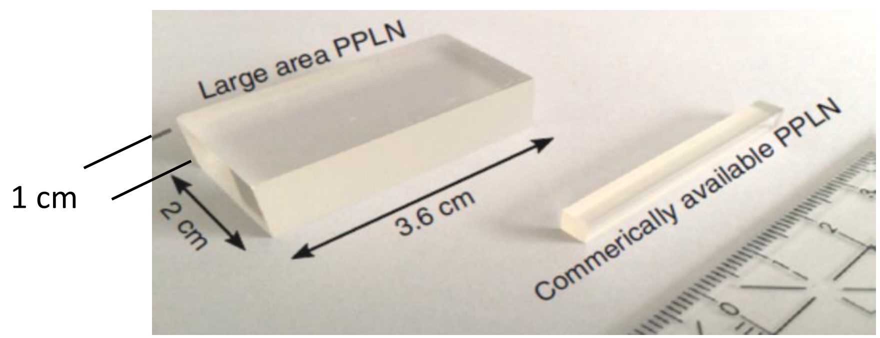
2. C. Weiss, Y. Avetisyan, R. Beigang, 1-st THz Workshop, Denmark,17-19 Sept. (2000).

PPLN from HC Photonic Corp. & Taira's group



Reproduced from S. Jolly, et al., Nat. Commun. **10**, 2591 (2019).

Performances of LN-based THz sources

Ref.	PRF (kHz)	e_L (mJ)	Pump pulse	ν_o (THz)	e_{THz} (μJ)	η (%)	Crystal, Temperature
[1]	1	1	$\Delta\nu$ -limited	0.5	1	0.1	PPLN, CrT
[2]	$5 \cdot 10^{-3}$	$\sim 10^3$	Chirp & Delay	0.54	40	0.13	PPLN, CrT
[3]	$5 \cdot 10^{-3}$	$\sim 10^3$	Chirp & Delay	0.36	600	0.24	LA-PPLN, CrT
[4]	10^{-2}	910	$\Delta\nu$ -limited	0.16	**1300**	0.14	Stack of 12-LN plate
[5]	$5 \cdot 10^{-3}$	20	TPF, *I*-modulated.	0.26	108	0.55	Prism-chape LN, RT
[6]	1	2.6	TPF, *I*-modulated	0.76	2.4	0.1	Prism-chape LN, RT
[7]	10^{-2}	6	DFG	0.53 0.29	12	0.2 **(0.9*)** (0.5*)	PPLN, CrT

1. S. Garbajo, et al. Opt. Lett. **40**, 5762 (2015).
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4. F. Lemery, et al. Commun. Phys **3**, 150 (2020).
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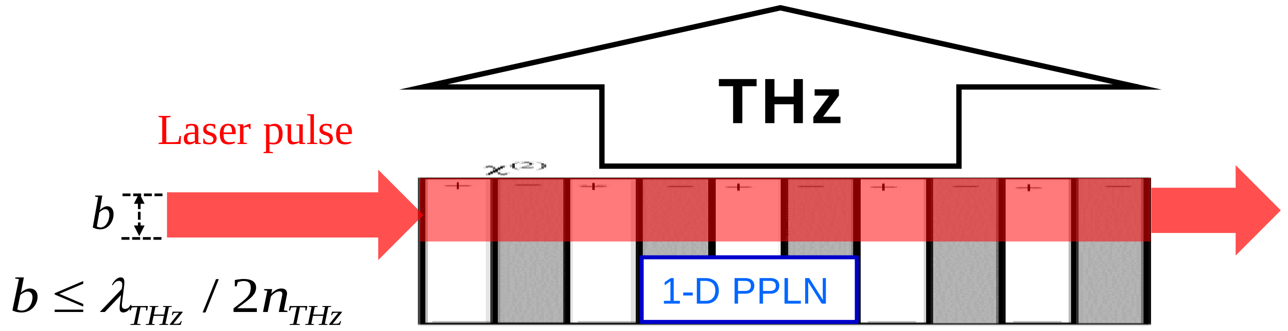
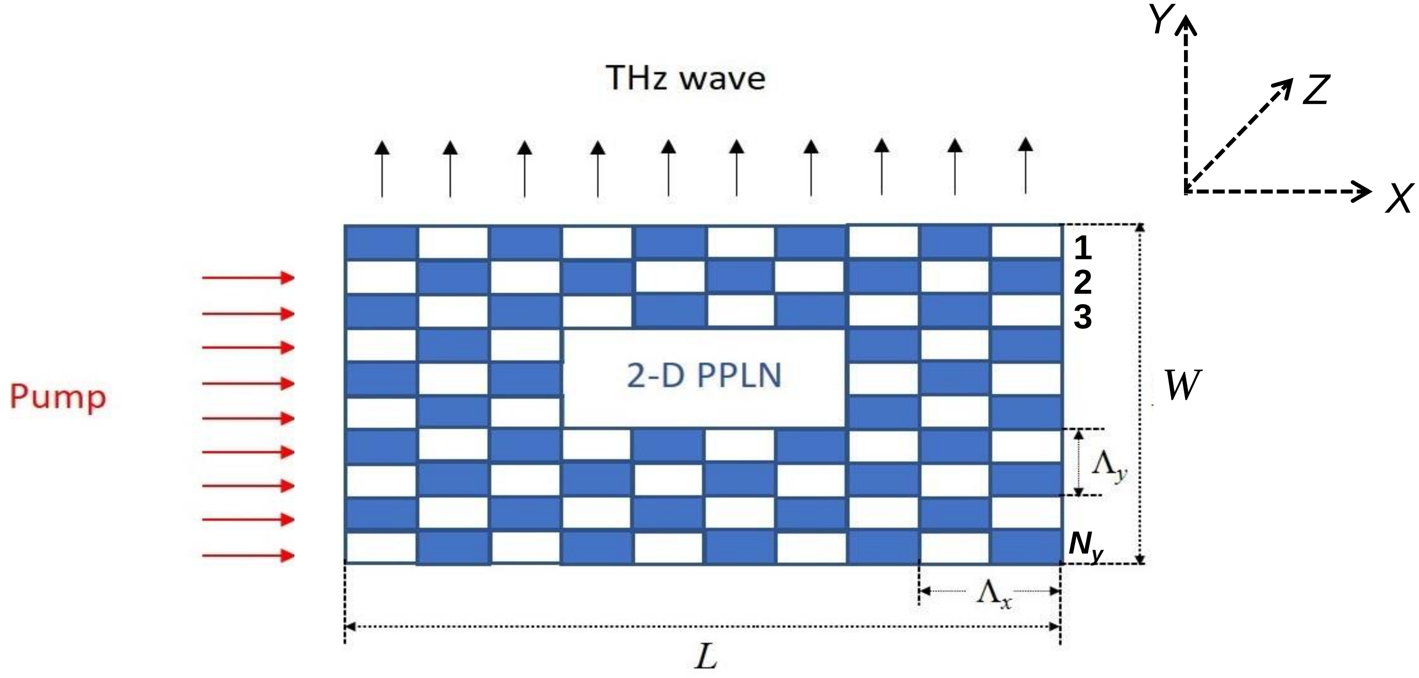
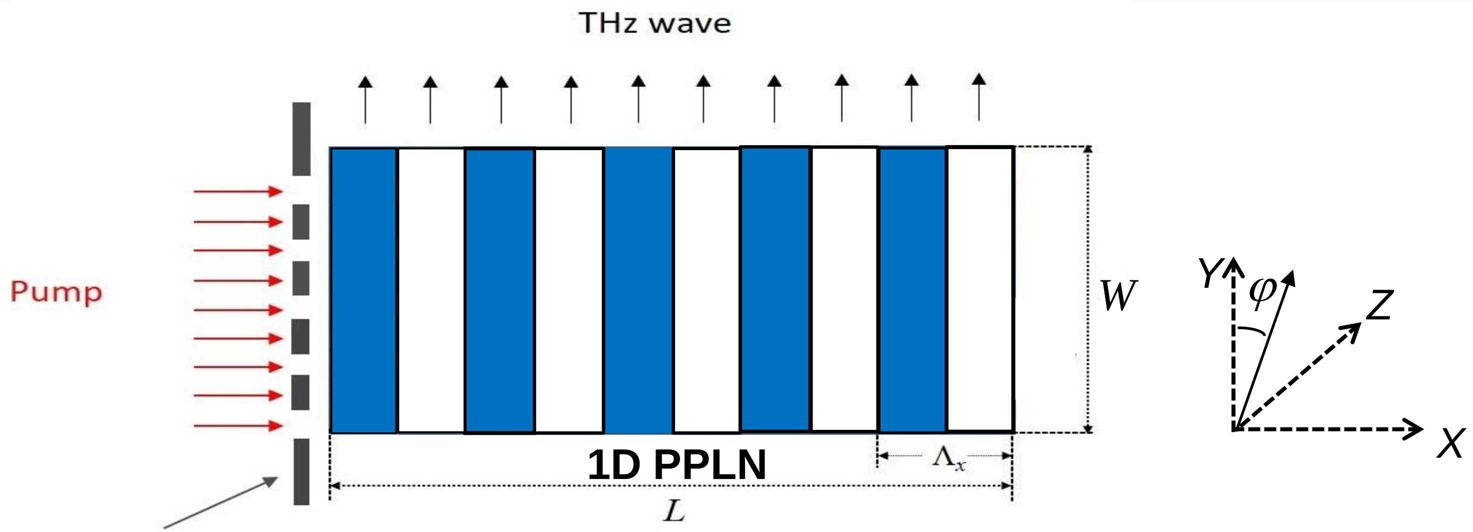
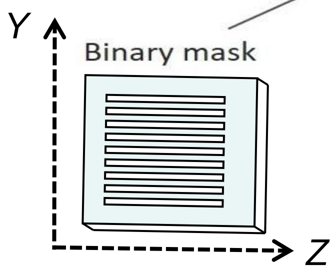
THz generation in 1D and 2D PPLNs





Forming 2D PPLN using a phase mask



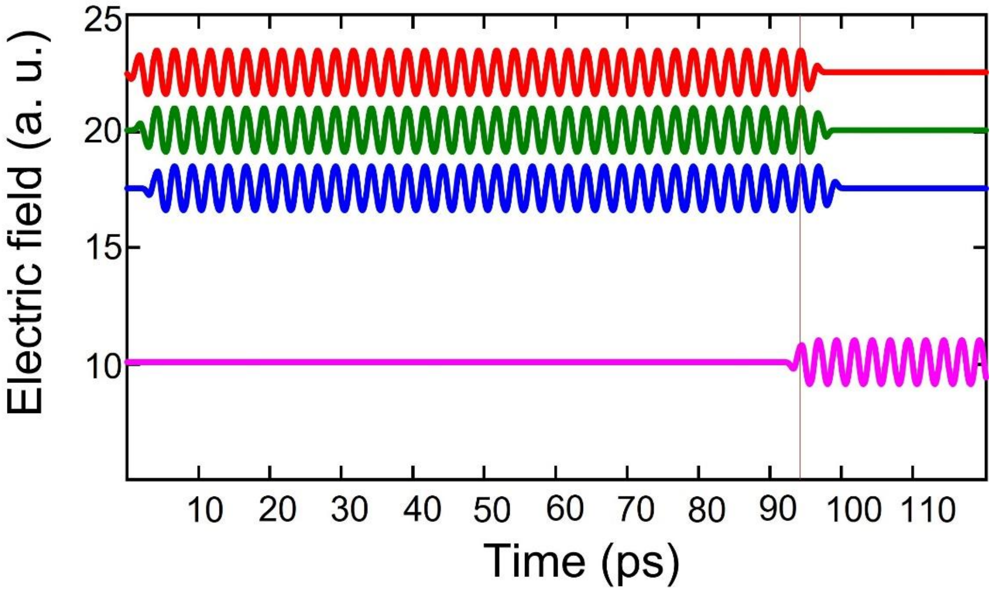


The laser pulses after passing through the dielectric base of the mask acquire delays of $\tau = T_0/2$, where T_0 is the designed period of THz-wave.

THz field calculation

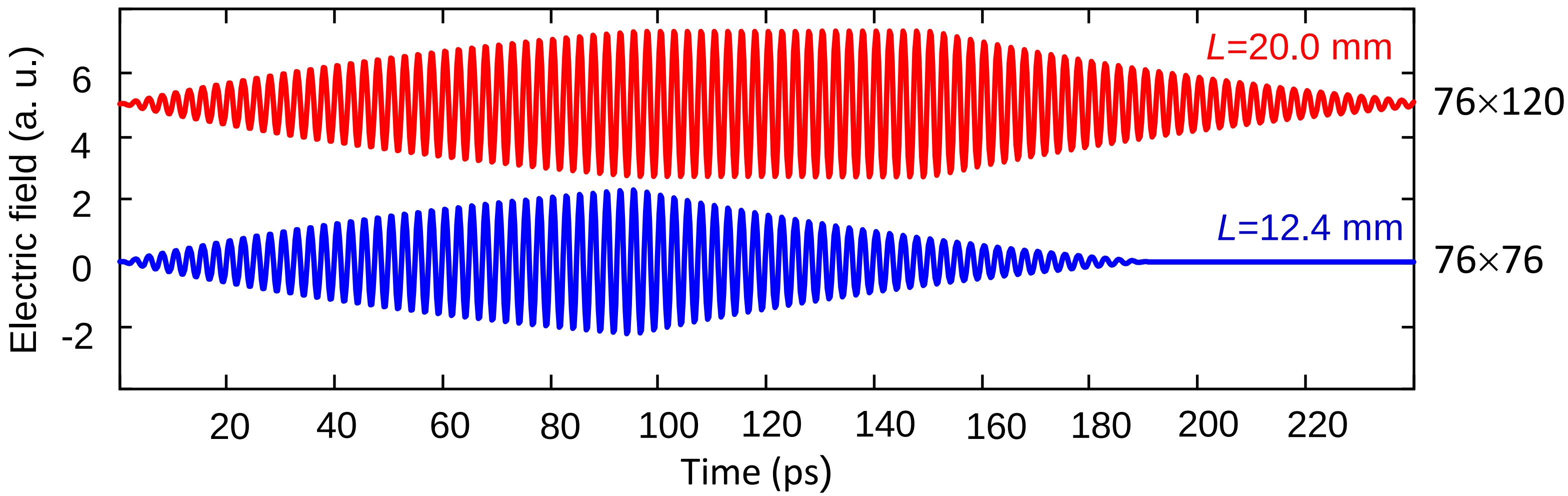
1. 4-mm-thick 2D PPLN is considered as ensemble of elementary 1D PPLN stacked along Y-axis. It is assumed that the spatial distribution of the pump beam intensity is uniform.
2. Surface-emitting THz field from 1D PPLN is calculated by neglecting pump pulse depletion and its spatial and temporal distortion in the crystal. The designed frequency of generation is **0.4 THz, the number of domains along Y-axis is N_y = 76 (period Λ_y = 147 μm), along *X*-axis is N_x = 76 and 120 (period Λ_x = 0.326 μm).** The pump pulse $\tau_{FWHM} \approx$ 1 ps. The THz absorption coefficient is α = 3.3 (1.8) cm^{-1} for T = 300 (100) K.

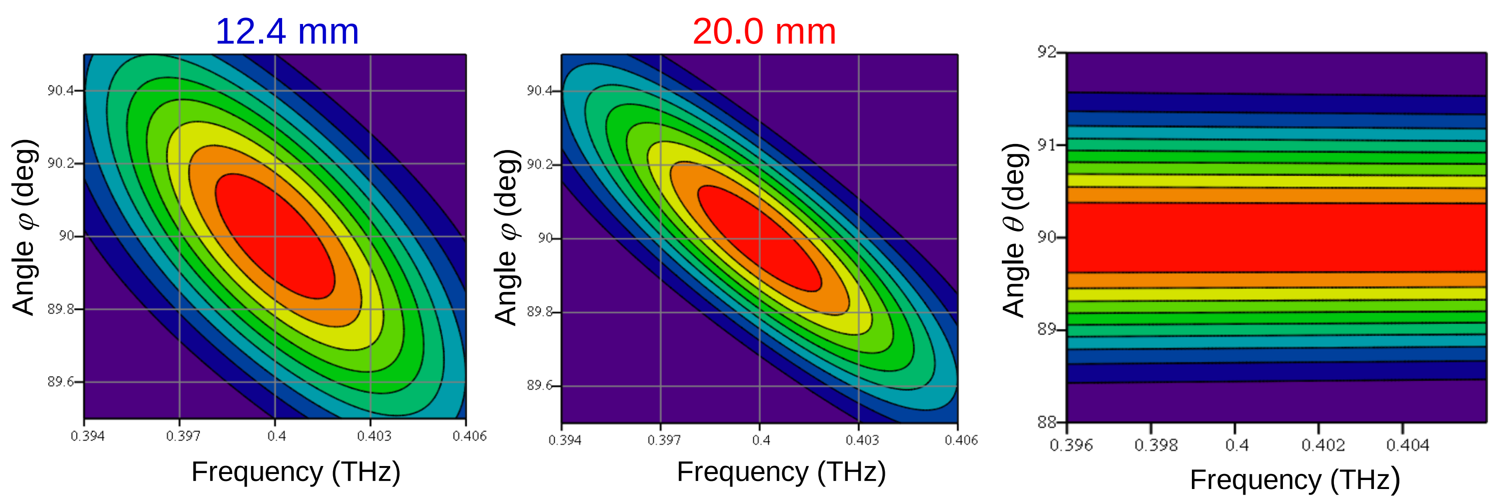
THz waveforms generated by the first (red line), second (green), third (blue) and the last (violet) elementary 1D APPLNs.



$N_x = N_y = 76$
$L = 12.4$ mm,
$W = 5.62$ mm

THz field from 2D PPLN





THz-pulse energy spectral density

$$e_{\mathrm{THz}} = \frac{n_{THz}}{\sqrt{\mu_0 / \varepsilon_0}} \int_{\omega}\int_{\varphi}\int_{\theta} 2\pi \left| E_{THz}(\omega,\theta,\varphi) \right|^2 R^2 d\omega d\varphi d\theta,$$

$E_{THz}(\omega,\theta,\varphi)$ is the Fourier transform of THz field.

Summary of Results

e_L (mJ)	Pump pulse	PPLN length, width (mm)	PPLN (K)	e_{THz} (μJ)	Effic. η* (%)	$\Delta\nu/\nu_o$ (%)
9.6	FTL	20, 5.62	300	8.1	0.085	< 1
9.6	FTL	12.4, 5.62	300	4.5	0.047	1.3
17.6	FTL	22.7, 10.3	100	27.7	0.16	< 1

* $\eta = e_{THz}/e_L \propto e_L$, if everything else being equal.

Conclusions

- A new scheme for generating narrow-band THz pulses in PPLN crystals using a phase mask is proposed and analyzed.
- The THz field, pulse energy, and radiation pattern are calculated using a radiating antenna model.
- The efficiency of THz generation can by increased by *N*-times using burst of *N* pump pulses or by *Q*-times using the resonance enhancement of pump intensity in optical cavity.

Thank you