A New Scheme of High-Energy THz Source Using Nonlinear Crystal with Attached Multistep Phase Mask

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OUTLINE

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2. Optical rectification in mask covered NLO crystals.
3. Masks design for $LiNbO_3$ and ZnTe crystals.
4. Results and discussions.
4. Conclusions.

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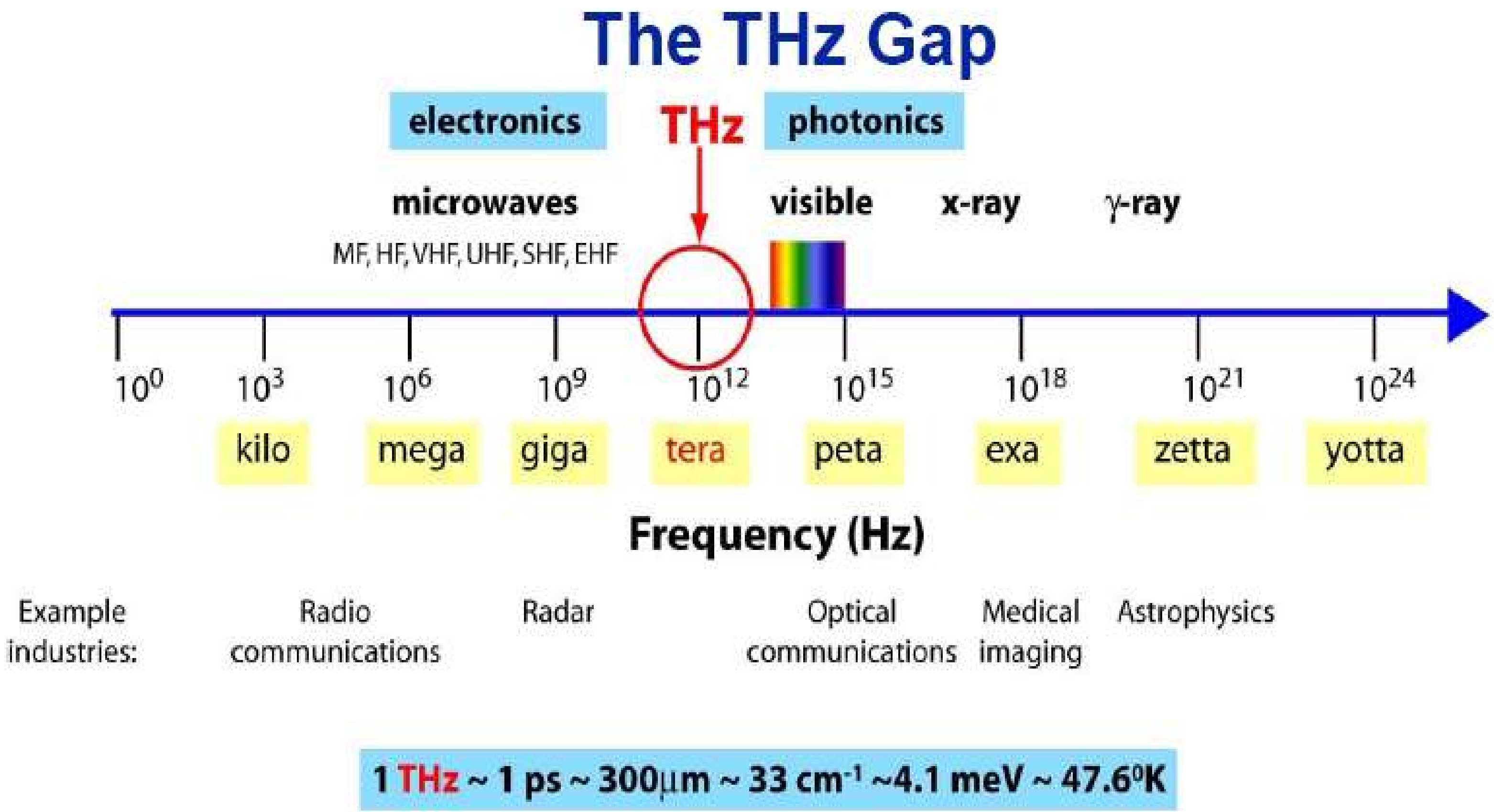
THZ region

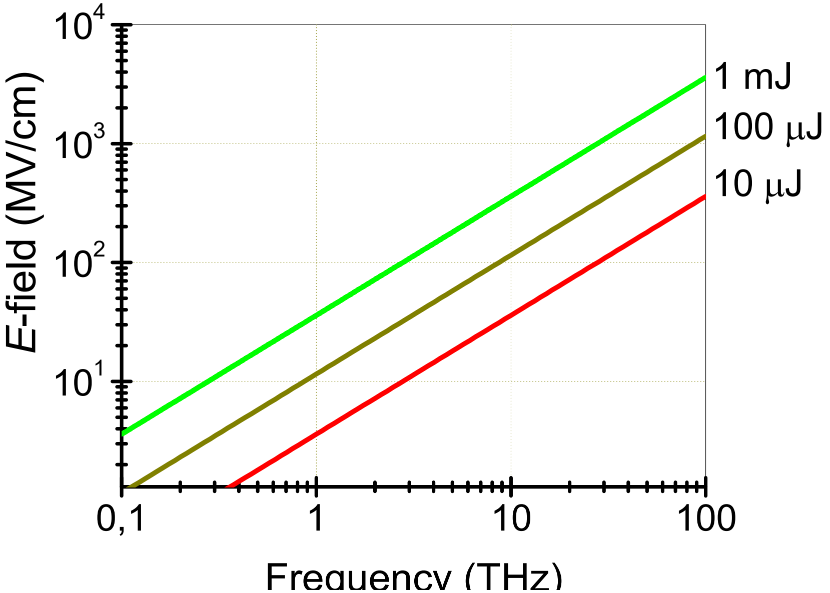

The THz Gap
electronics
THz
photonics
microwaves
MF, HF, VHF, UHF, SHF, EHF
visible
x-ray
γ-ray
10^0
10^3
10^6
10^9
10^{12}
10^{15}
10^{18}
10^{21}
10^{24}
kilo
mega
giga
tera
peta
exa
zetta
yotta
Frequency (Hz)
Example industries:
Radio communications
Radar
Optical communications
Medical imaging
Astrophysics
1 THz ~ 1 ps ~ 300μm ~ 33 cm^{-1} ~4.1 meV ~ 47.6^0K

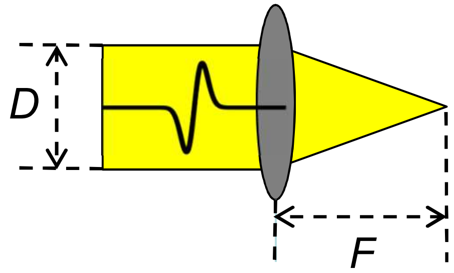
Attractive features of THz waves

- ***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 terabits-per-second.

Applications of strong THz-field in research

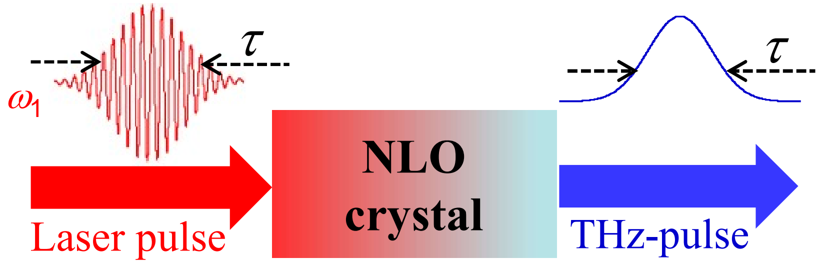
- **Nonlinear optics investigation at THz frequencies.**
- **THz time-domain nonlinear spectroscopy.**
- **Acceleration of charged particles & THz driven undulator for X-ray.**
  (AXSIS project under development in DESY).
- **Control and measurements of electron bunch.**

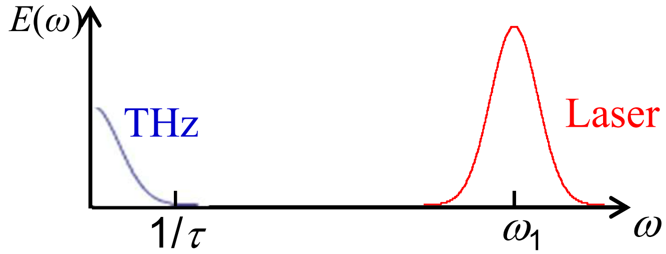




Optical rectification in NLO crystal

$$P(t) = \varepsilon_0 \left(\alpha E + 2dE^2 + \gamma E^3 + \cdots \right) \qquad E = \mathrm{Re}\left(E_0(t) e^{i\omega_0 t} \right)$$





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

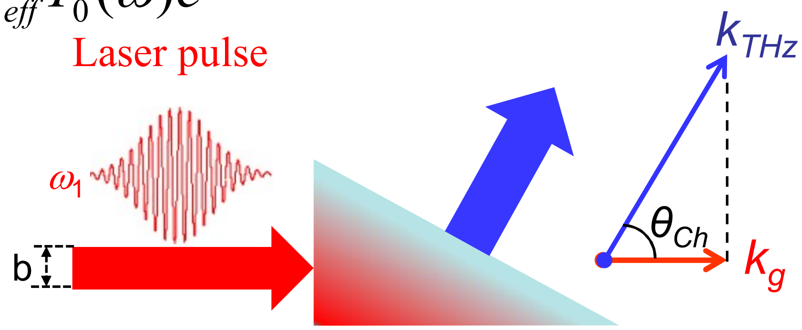
$k_{THz} = \omega / v_{THz}$

$k_g = \omega / u_g$

$v_{THz} = c/n_{THz}$, $u_g = c/n_g$ $\Rightarrow$ $n_{THz} = n_g$

$$P_{NL}(t) \sim d_{eff} I_0(\omega) e^{-ik_g z}$$

Laser pulse

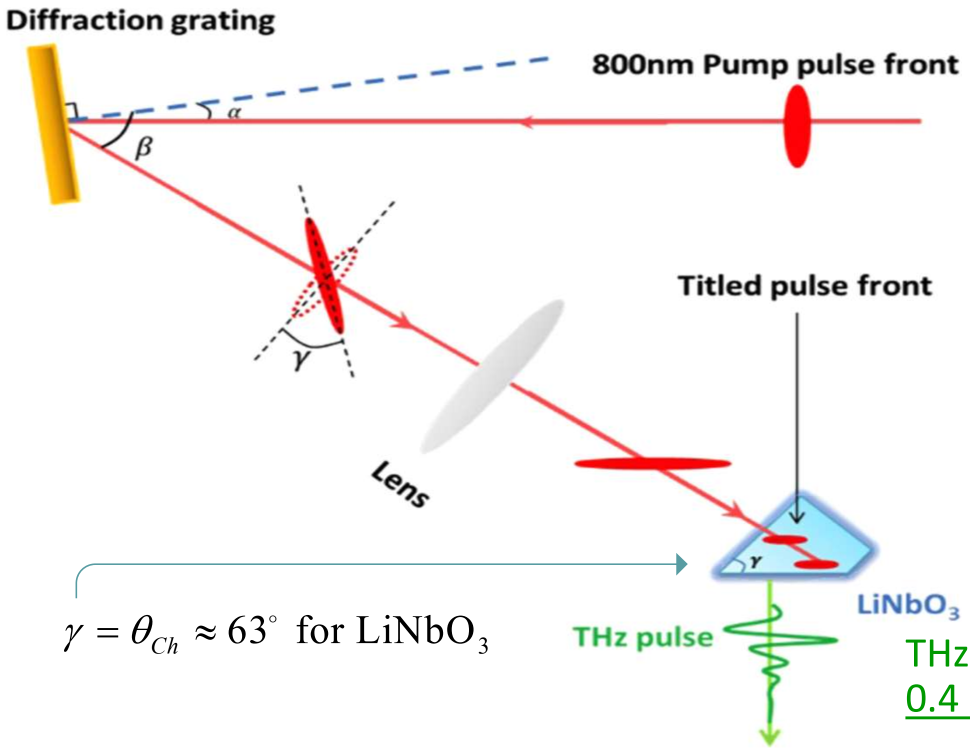


$$\cos\theta_{Ch} = v_{THz}/u_g = n_g/n_{THz}$$

$$b << \frac{\lambda_{THz}}{2 n_{THz} \sin\theta_{Ch}} \approx 33\mu m$$

Tilted pulse-front pumping

The use of large-aperture optical beam for PM THz generation is possible using TPFP technique [1].



$\gamma = \theta_{Ch} \approx 63^{\circ}$ for $LiNbO_3$

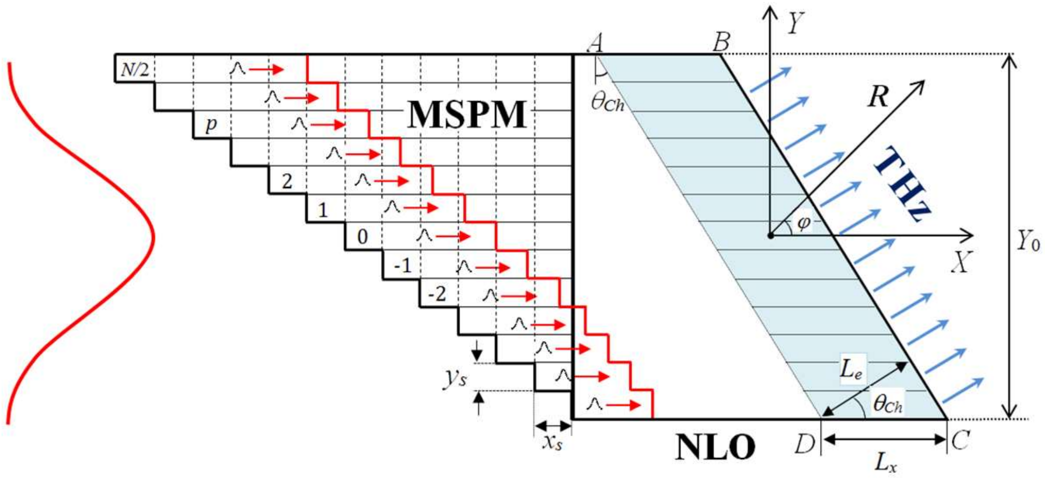
J. Hebling, et al. Opt. Lett. **10**, 1161, (2002).

J. Fülöp, et al. Opt. Exp. **22**, 20155, (2014).

THz pulses with energy <u>0.4 mJ</u> were obtained [2].

Further increase is challenging because of serious limitations: imaging errors in crystal and temporal broadening of the pump pulse.

THz in NLO crystal with MSPM



$\theta_{Ch} = \cos^{-1}(n_g/n_{THz})$

$$E_p(\nu) = A d_{eff} \nu I_p(\nu) y_s \mathrm{sinc}\left(\frac{\pi y_s}{2 l_c(\nu)}\right), \quad l_c(\nu) = \frac{c}{2\nu n_{THz} \sin\theta_{Ch}}, \quad I_p(\nu) = \sqrt{\pi}\tau_L I_0 e^{-\pi^2\nu^2\tau_L^2} e^{-i2\pi\nu\tau}$$

$= 2/\pi$ at $y_s = l_c(1\mathrm{THz}) \equiv y_0$

$$\tau = x_s(n_{gm} - 1)/c$$

$$y_0 = \frac{150}{\sqrt{n_{THz}^2 - n_g^2}} \ [\mu\mathrm{m}], \qquad x_0 = \frac{150}{n_{gm} - 1} \ [\mu\mathrm{m}].$$

THz-pulse in the far-field

$$E_{THz}(\omega,\varphi)=\sum_{p=-N/2}^{N/2}E_{zp}(\omega,\varphi)\approx\frac{Ae^{-ikR}d_{eff}y_0r_yI_0e^{-\frac{\omega^2\tau_L^2}{4}}}{R_0}L_x\mathrm{sinc}\left(\frac{\Delta kL_x}{2}\right)\Phi(\omega,\varphi),$$

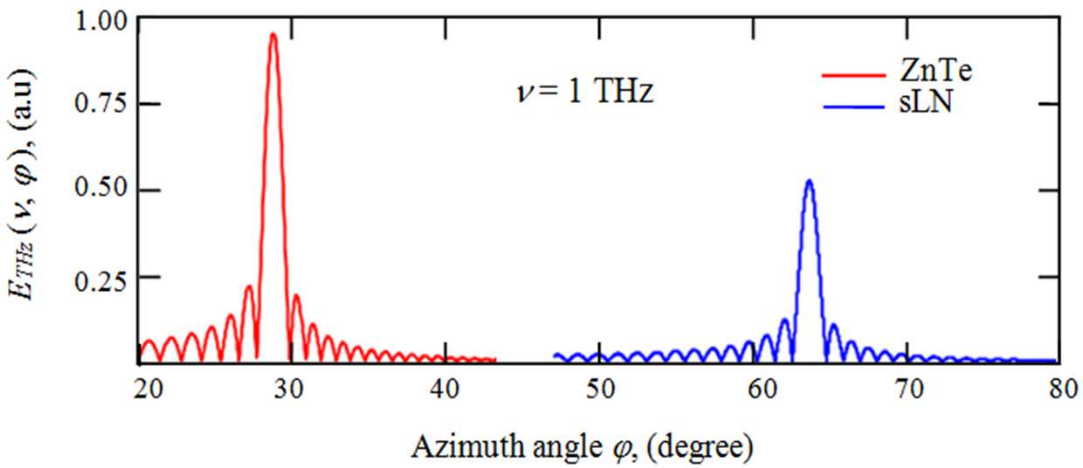
with $$\Phi(\omega,\varphi)=\sum_{p=-N/2}^{N/2}\exp\left\{ip\left[\frac{\omega}{c}n_T(\omega)y_0\sin\varphi-\Delta ky_0\tan\theta_{Ch}-x_0\left(n_{gm}-1\right)\right]\right\}\exp\left[-2\left(py_0/r_y\right)^2\right].$$

NLO	λ_{pump} [μm]	d_{eff} [pm/V]	x_0 [μm]	y_0 [μm]	R_{el} [mm]	N	r_y [mm]	I_{av} [GW/cm^2]	α (1 THz) [cm^{-1}]
ZnTe	1.7	68.5	200	98.0	31	30	1.5	13.5 [1]	2.2
LN	1.03	168	200	33.7	6	30	0.5	20 [2, 3]	13

[1]. Gy. Polónyi et al. Opt. Express **24**, 23872 (2016).
[2]. M.C. Hoffmann, K.-L. Yeh, J. Hebling, and K. A. Nelson, Opt. Express **15**, 11706 (2007).
[3]. K. Ravi, W. R. Huang, S. Carbajo, X. Wu, and F. X. Kärtner, Opt. Express 22, 20239 (2014).

THz radiation pattern

THz electric field in the frequency domain at 1 THz.

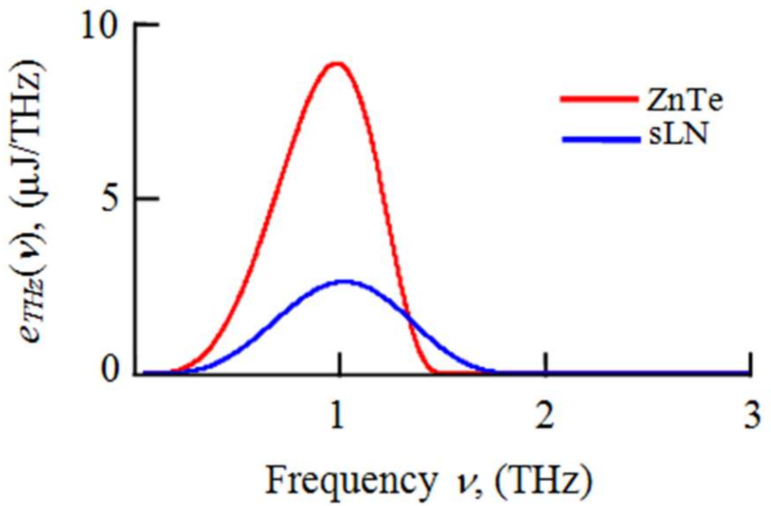


φ_m = 28.7° and 63.6° for ZnTe and LN

$\Delta\varphi \approx 1°$ for both ZnTe and LN crystals

THz-pulse energy spectral density

$$\varepsilon_{THz}(\omega) = \frac{n_{THz}}{4\pi W}\left|E_{THz}(\omega,\theta_{Ch})\right|^2 R^2 \Delta\varphi \Delta\theta_z ,$$



$Э_{THz}$ = 10.5 μJ and 4.1μJ for ZnTe and LN

ε_L = 0,9 mJ and 0,5 mJ for ZnTe and LN

Conclusions

- **A new scheme of high-energy THz pulse generation in ZnTe an LN crystals based on using MSPM is proposed and analyzed.**
- **The design of MSPM is performed.**
- **The THz field is analytically calculated using radiating antenna model.**
- **The ZnTe crystal allows obtaining higher THz-pulse energy than that of LN crystal, especially when long-wavelength pump sources are used.**

Thank you