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SZENTAGOTHAI RESEARCH CENTRE

THz source development at the University of Pécs

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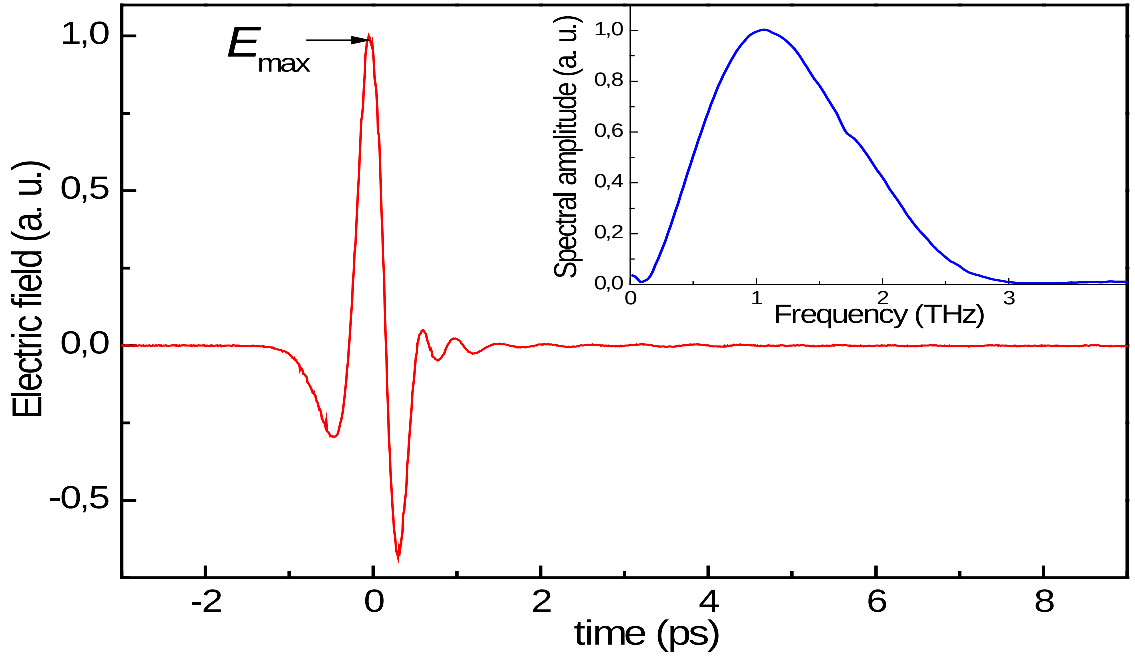
HIGH-FIELD THz LAB

TERAFLAG Workshop, Cassis, France, 6 September 2018

Classification of THz pulses by peak electric field and energy

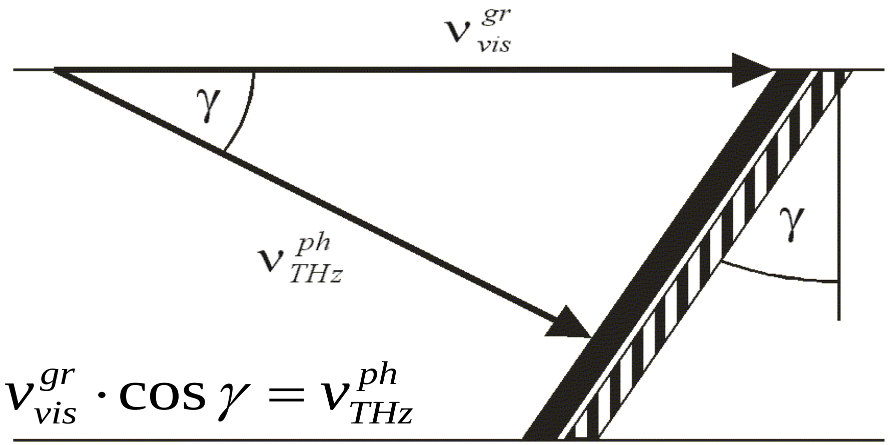
Motivation



- Linear (TDTS) THz spectroscopy (E_{max} ≈ 100 V/cm → 10 fJ energy)
- High field THz pulses (E_{max} ≈ 100 kV/cm → 1 μJ energy)
  THz pump – probe measurement, nonlinear THz optics
- Extreme high field THz pulses (E_{max} ≈ 100 MV/cm → 10 mJ energy)

enhancement of HHG for attosecond pulse generation, orientation of molecules, particle acceleration and manipulation, CEP stable attosecond pulse generation, etc.

Velocity matching by tilted-pulse-front pumping



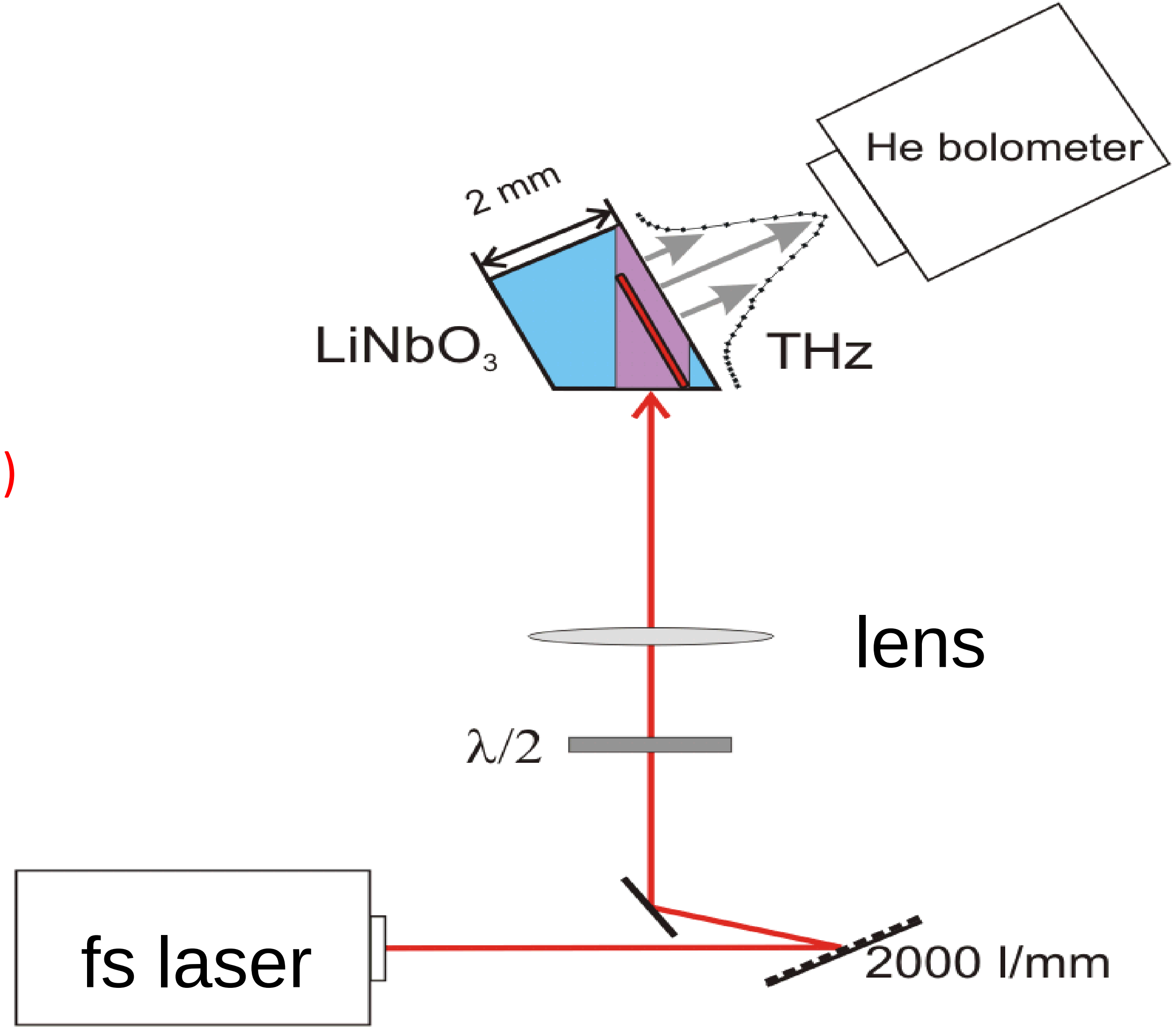
Hebling et al., Opt. Expr. **10**, 1161 (2002)

For LN $\gamma = 63^{\circ}$

$$\tan\gamma = -\frac{n}{n_g}\lambda\frac{d\varepsilon}{d\lambda}$$

pulse front tilt

angular dispersion



Success of TPFP $LiNbO_3$ THz sources

Large nonlinear coefficient of LN

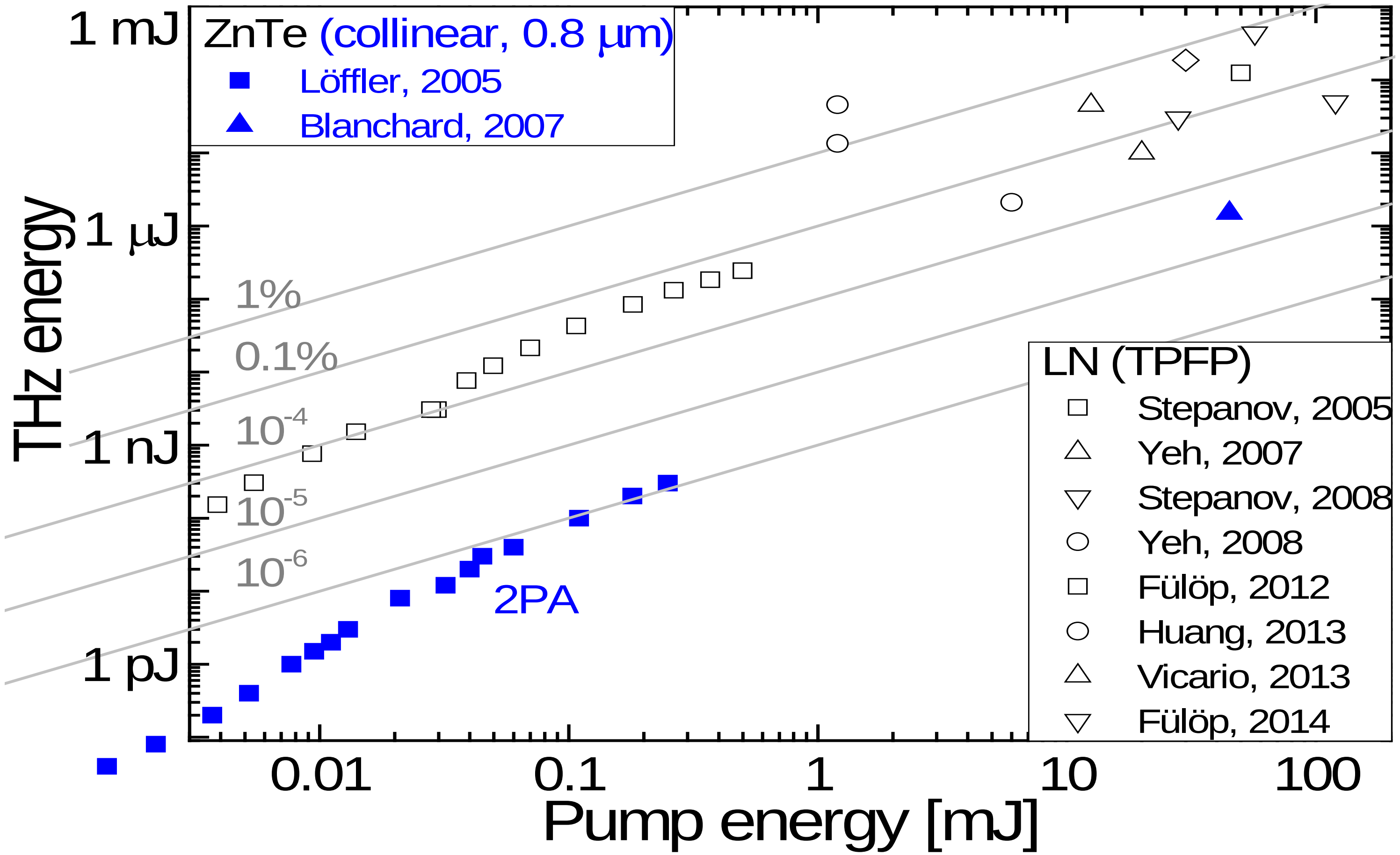
Material	ZnTe	GaP	GaAs	LN
d_{eff} [pm/V]	68.5	24.8	65.6	168

Large bandgap, absence of low-order multi-photon absorption (MPA)

Very efficient THz pulse source on the 0.2 – 2 THz range

μJ level THz energy is enough for pump in pump – probe and control experiments

Particle acceleration needs a few mJ THz energy



Limitations of TPFP in LN

Elimination/mitigation of the limitations

- **Limited interaction** length due to large angular dispersion ($\gamma \approx 63°$)

$$\tan\gamma = -\frac{n}{n_g}\lambda\frac{d\varepsilon}{d\lambda} \qquad D = \frac{d\left(v_g^{-1}\right)}{d\lambda} = \frac{\lambda}{c}\left[n\left(\frac{d\varepsilon}{d\lambda}\right)^2 - \frac{d^2 n}{d\lambda^2}\right]$$

Using longer pump pulses J. A. Fülöp et al., Opt. Express, **18**, 12311 (2010)

Using segmented TPF (reflection echelon) B. K. Ofori-Okai et al.: Opt. Express **24**, 5057 (2016)

- **Imaging errors** at large spot sizes

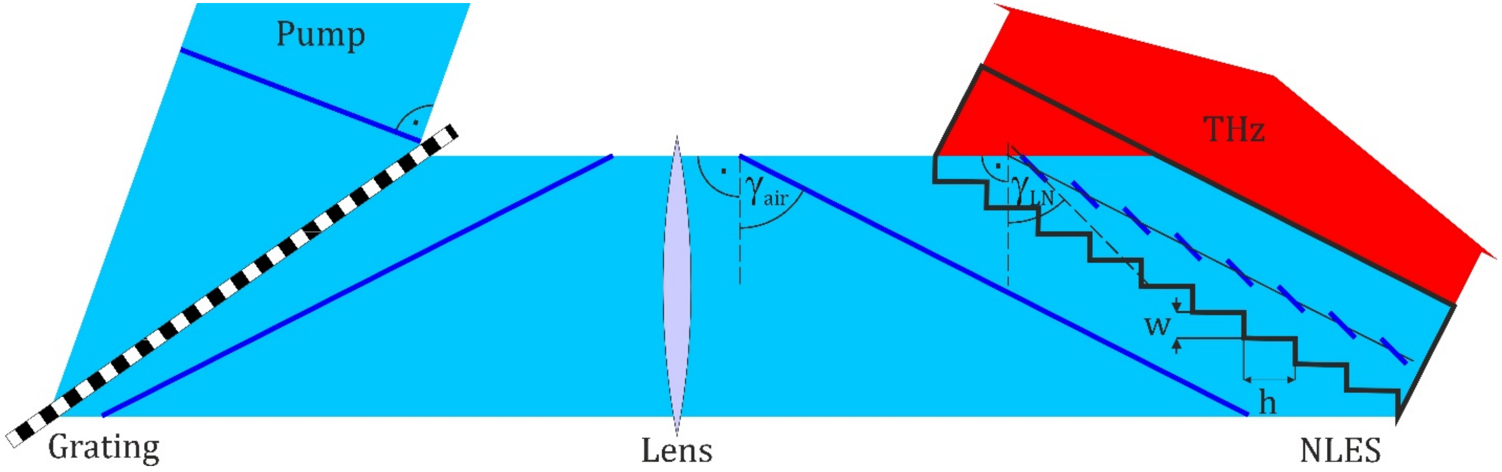
Contact grating L. Pálfalvi et al., Appl. Phys. Lett. **92**, 171107 (2008)

Hybrid TPFP scheme L. Pálfalvi et al., Opt. Express 24, 8156 (2016)

- **Prism shaped LN crystal** with large wedge angle leads to THz pulse and beam distortions

Nonlinear echelon slab (NLES) based hybrid TPFP scheme L. Pálfalvi et al.: Optics Express **25,** 29560 (2017)

Hybrid TPFP with NLES



$\gamma_{pretilt} = \gamma_{air} = 62^o$

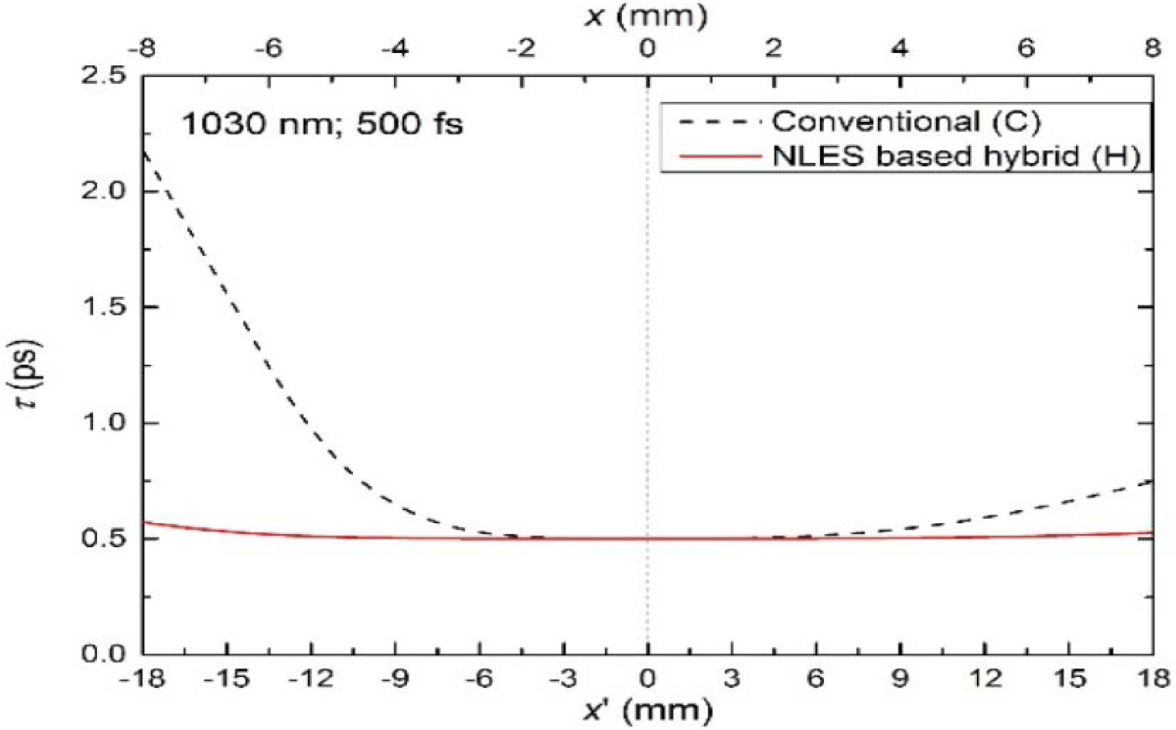
$\gamma_{air,conv} = 76^o$,

$L_{interaction} \sim (1/\tan\gamma_{air})^2$

4.55 x increase in $L_{interaction}$

w = 50 μm, h = 92 μm; $\gamma_{LN} = \gamma_{pretilt} = \gamma$

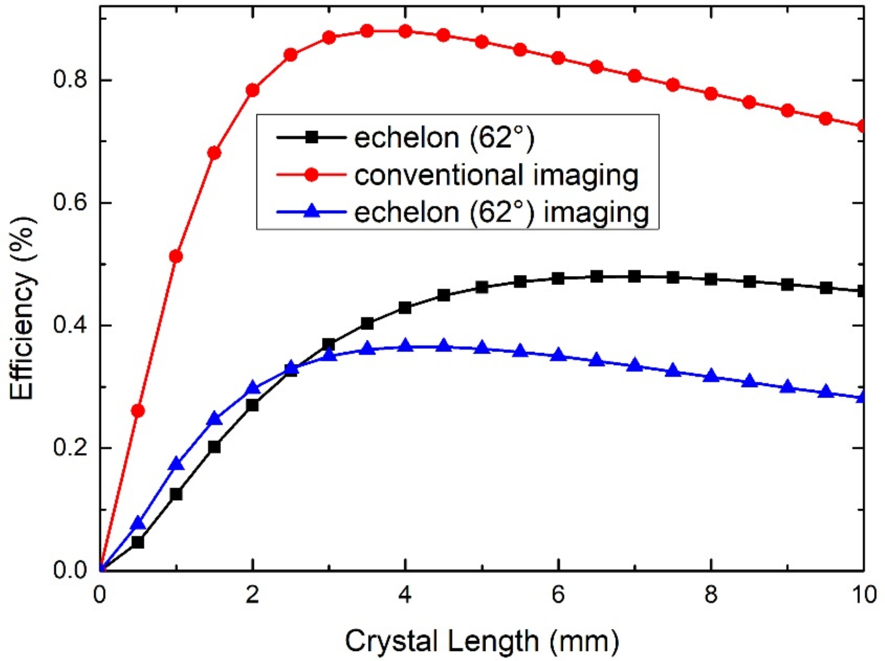
- Plan-parallel nonlinear crystal
- 4.55 x increase in $L_{interaction}$
- Significantly reduced imaging error

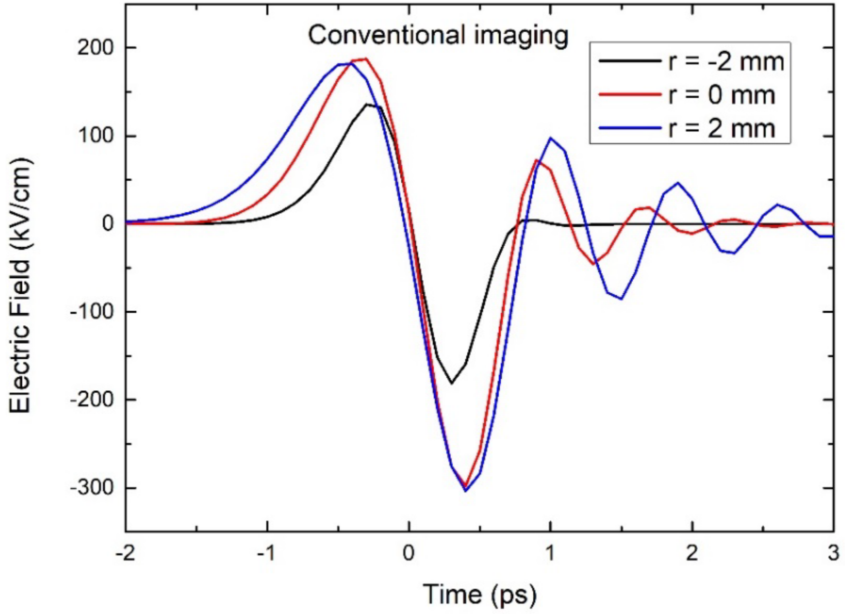


L. Pálfalvi et al.: Optics Express **25,** 29560 (2017)

Hybrid TPFP with NLES

Results of simulations

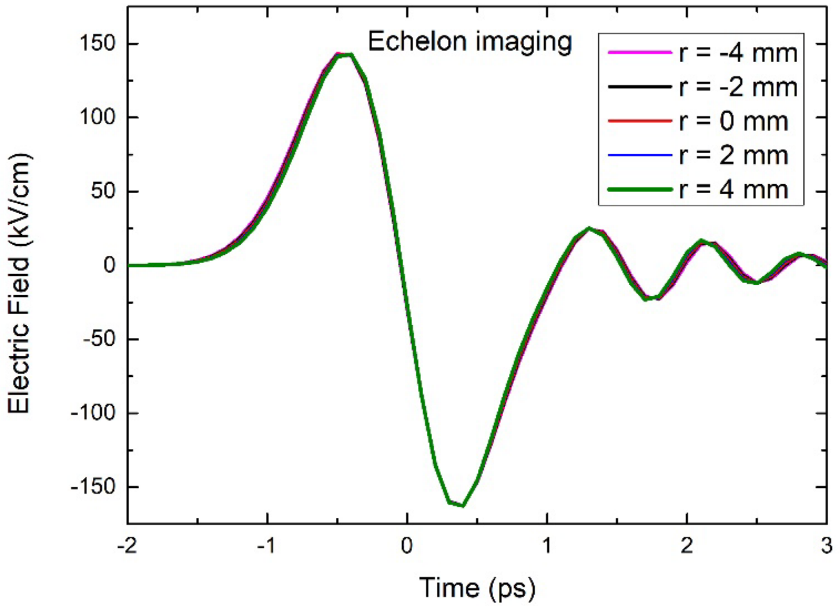




λ_p=1030 nm, I_p= 40 GW/cm^2, Δt_p= 200 fs, T=300 K, w=50 μm

$\eta_{NLES} = 0.41\ \eta_{Conv}$

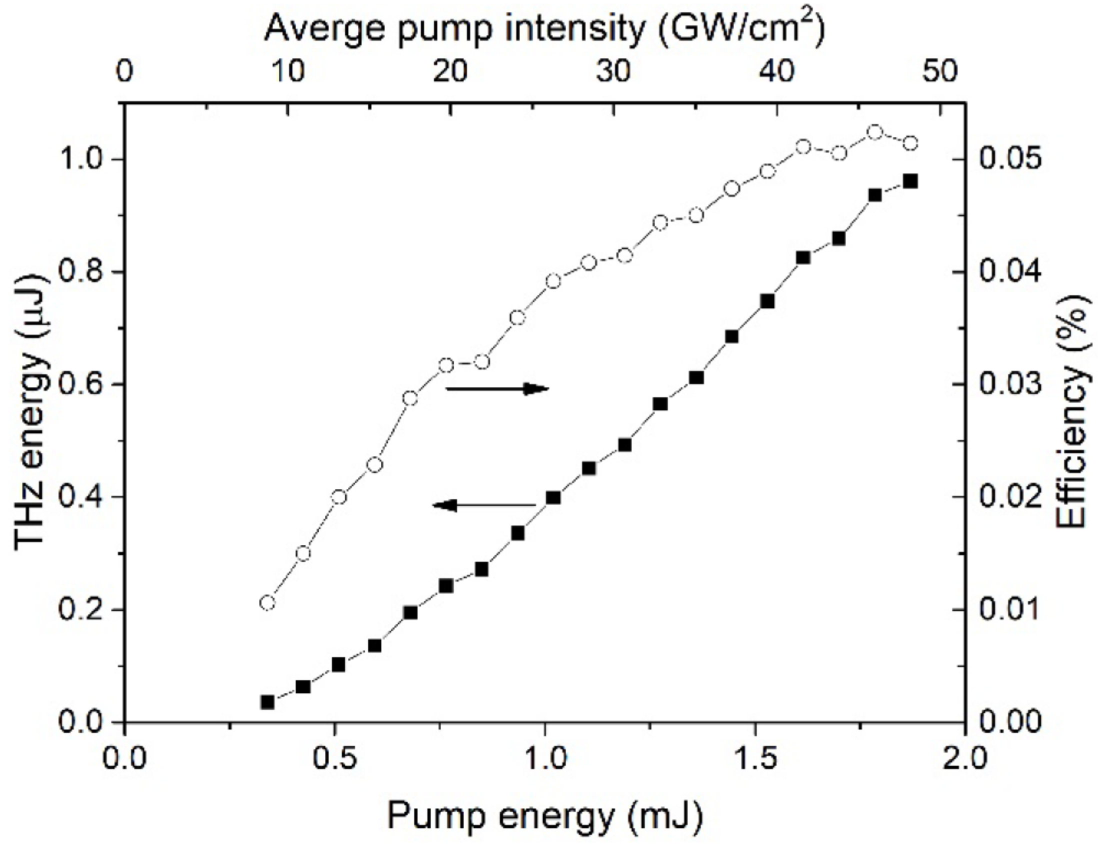
Perfectly spatially independent THz field shape



Gy. Tóth et al.: Optics Express, in preparation

Work of principle experiment with hybrid NLES setup

Results



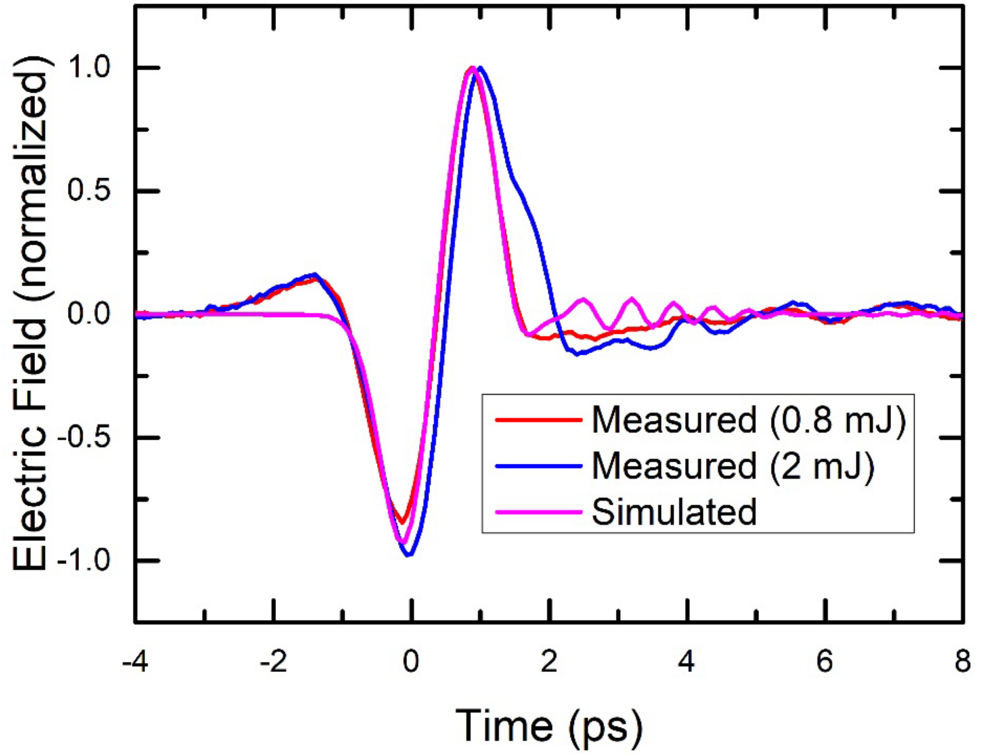
Preliminary results: 1.2 μJ THz

η > 0.05 % at 300 K

$\eta_{NLES} \approx 0.3\ \eta_{Conv}$, 30 % less than predicted

Small transversal size of NLES responsible to 50% drop of efficiency

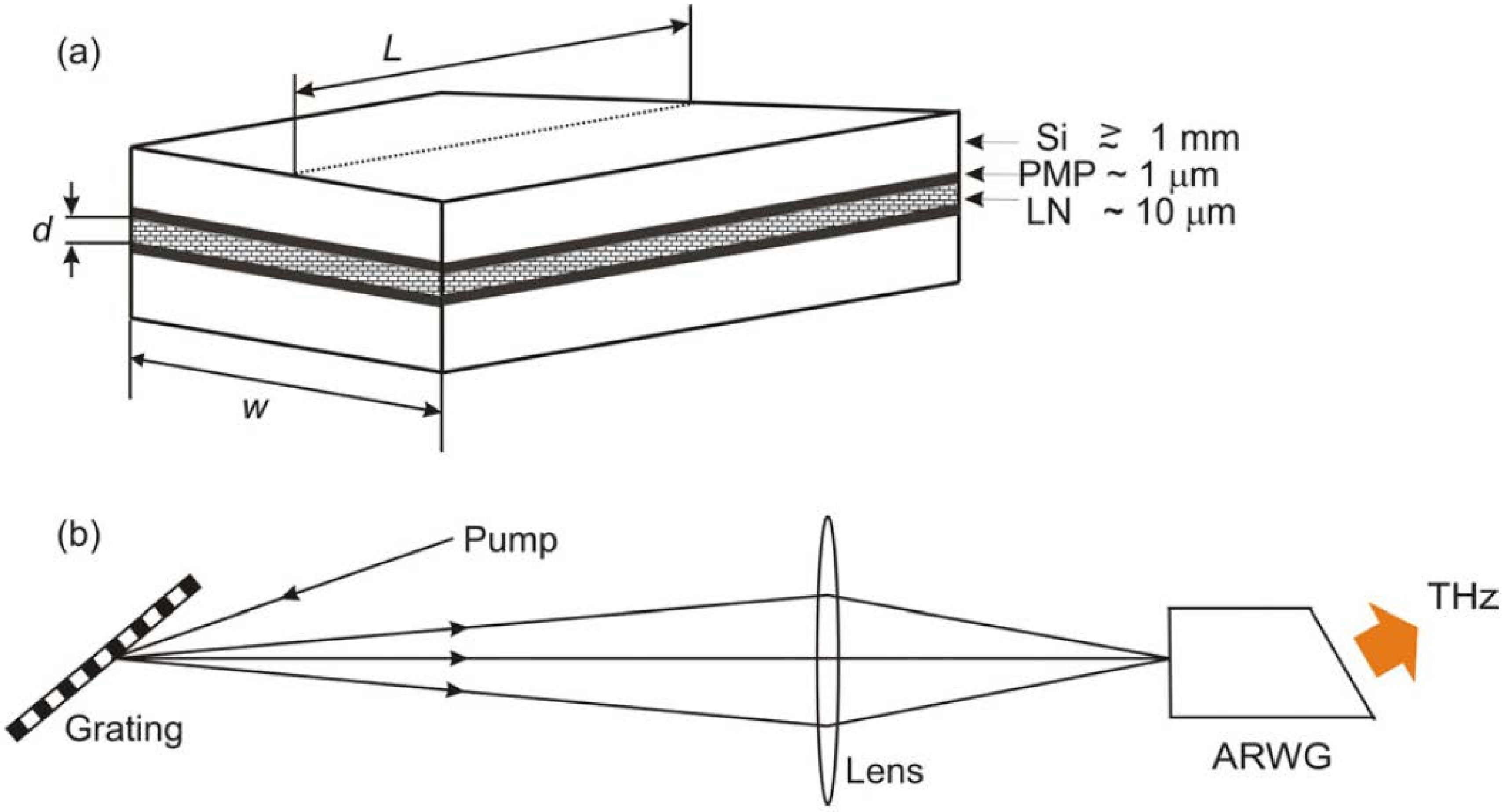
Perfect single-cycle THz pulse shape



1 mJ THz predicted at T = 100 K for 100 mJ pump from 1 inch diameter LN with η = 1 %

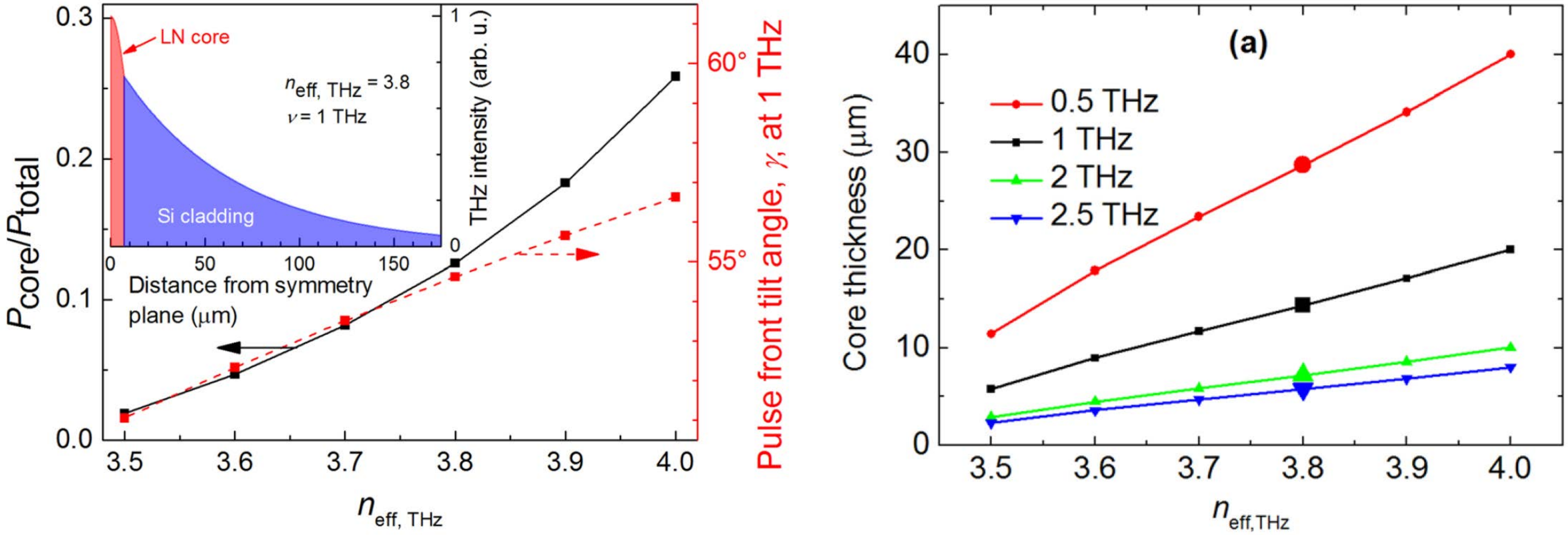
P.S. Nugraha et al.: Optics Lett. submitted

Absorption-reduced waveguide (ARWG) structure for efficient THz generation



L. Pálfalfi et al.: Appl. Phys. Lett. **107**, 233507 (2015)

ARWG structure for efficient THz generation



L. Pálfalfi et al.: Appl. Phys. Lett. **107**, 233507 (2015)

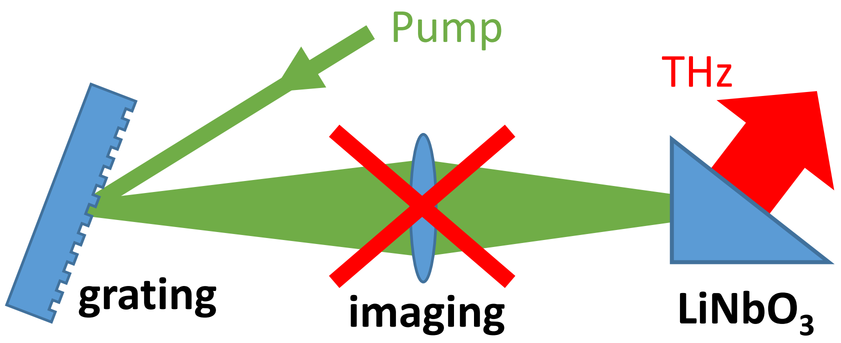
ARWG structure for efficient THz generation

Pump	Energy (μJ)	0.01	0.1	1	5
	Repetition rate (MHz)	100	10	1	1
	Pulse duration (fs)	100	200	300	300
	Average power (W)	1	1	1	5
	Average intensity (kW/cm^2)	40	40	30	30
	Peak intensity (GW/cm^2)	4	20	100	100
ARWG	LN core thickness (μm)	5	9	15	15
	Minimum LN core width (w) (mm)	1.8	1.0	0.8	4.1
	ARWG length (L) (mm)	5	5	5	5
THz radiation	THz spectral peak (THz)	1.35	0.92	0.71	0.71
	THz energy (nJ)	6.6×10^{-2}	3.2	95	477
	THz average power (mW)	6.6	32	95	477
	Efficiency enhancement factor (η_{ARWG}/η_{bulk})	22×	6.6×	2.5×	2.5×
	Spectral intensity enhancement factor	53×	18×	7.6×	7.6×

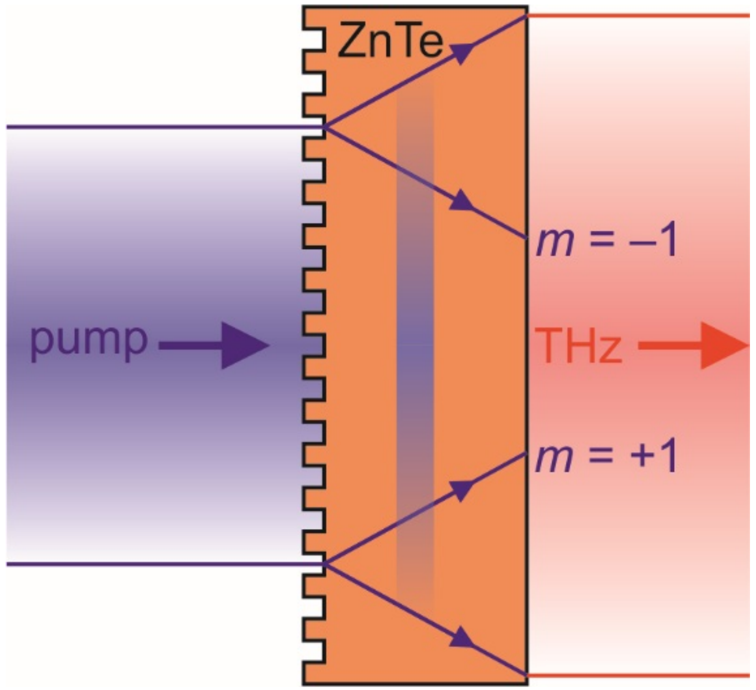
L. Pálfalfi et al.: Appl. Phys. Lett. **107**, 233507 (2015)

ZnTe contact-grating THz source

Very effective compact THz source



Conventional TPFP (with imaging)



TPFP with contact grating (no imaging)

L. Pálfalvi et al., Appl. Phys. Lett. **92**, 171107 (2008)

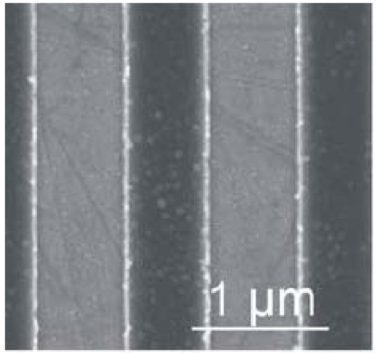
- Collinear geometry possible
  (with symmetrically propagating diffraction orders *m* = ±1)

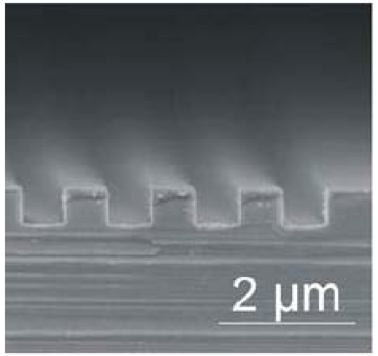
  Bakunov et al., J. Opt. Soc. Am. B, 2014

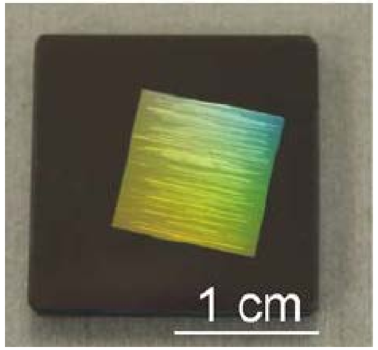
- THz energy easily increased by using larger pumped area
- Excellent THz beam quality

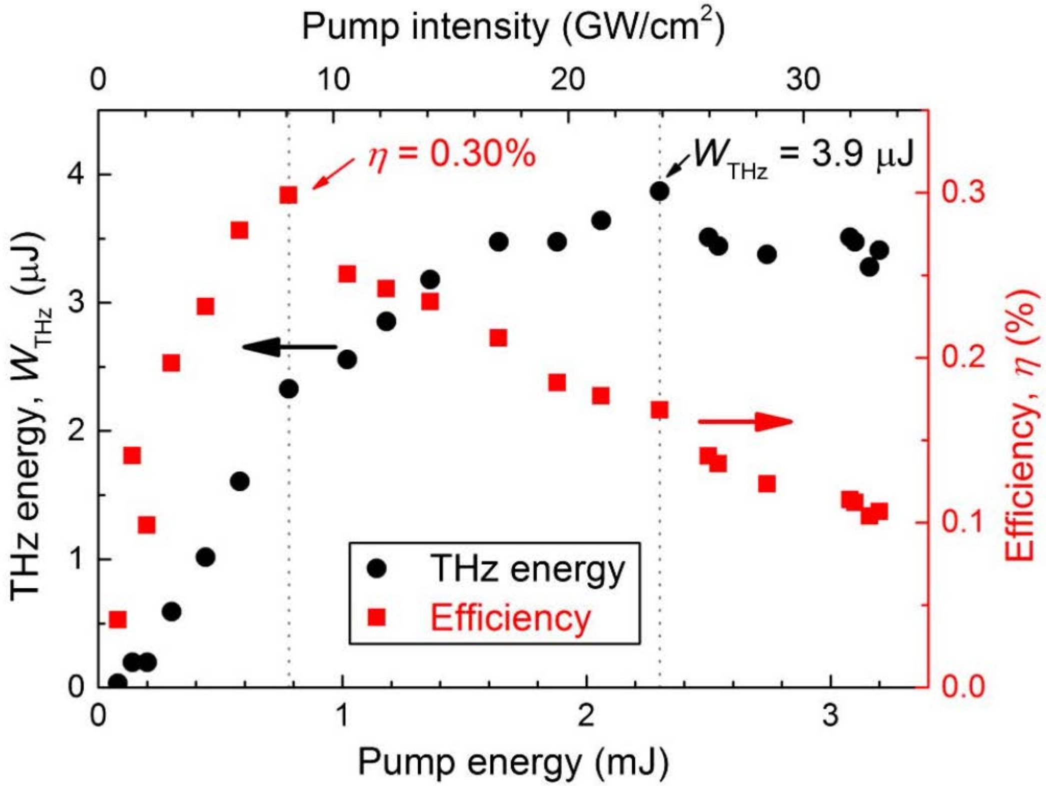
ZnTe contact-grating THz source

Very effective compact THz source









X100 efficiency compared to 800 nm pumped ZnTe

X10 efficiency compared to 2 µm pumped GaAs

J. A. Fülöp et al., Optica **3**, 1075 (2016)

Gy. Polónyi et al.: IEEE JSTQE **23**, 8501208 (2017) GaP $\eta = 2\%$

Multi-cycle: P. S. Nugraha et al.: J. Phys. B **51**, 094007 (2018),

G. Krizsán et al.: EOS-TST 2018, poster, GaP up to $\eta = 7\%$

Source of pump pulses (DCOPA) Gy. Tóth et al.: Opt. Express **25**, 28258 (2017)

Gy Tóth et al.: EOS-TST 2018, poster $\eta = 50\%$