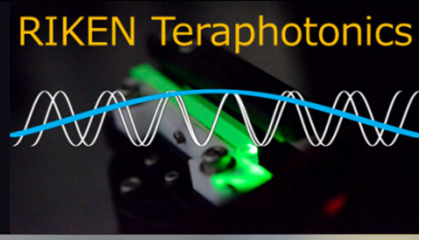


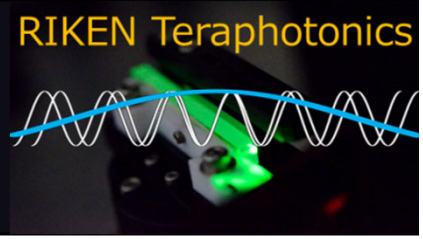
High-intesity 300-GHz Terahertz-wave generation based on nonlinear optical down-conversion

Hiroaki MINAMIDE,

Teraphotonics Research Team

RIKEN Center for Advanced Photonics, RIKEN

Outline



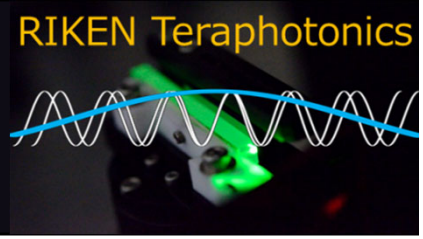
1. Introduction
   - Background & Motivation

2. Backward Terahertz-wave Parametric Oscillation
   - Slant-stripe-type PPLN crystal
   - Advantageous property

3. Experimental results of BW-TPO
   - Stable emission by injection-seeding for idler wave
   - High-brightness output by cascading process
   - Stable 2D imaging measurement toward 3D imaging

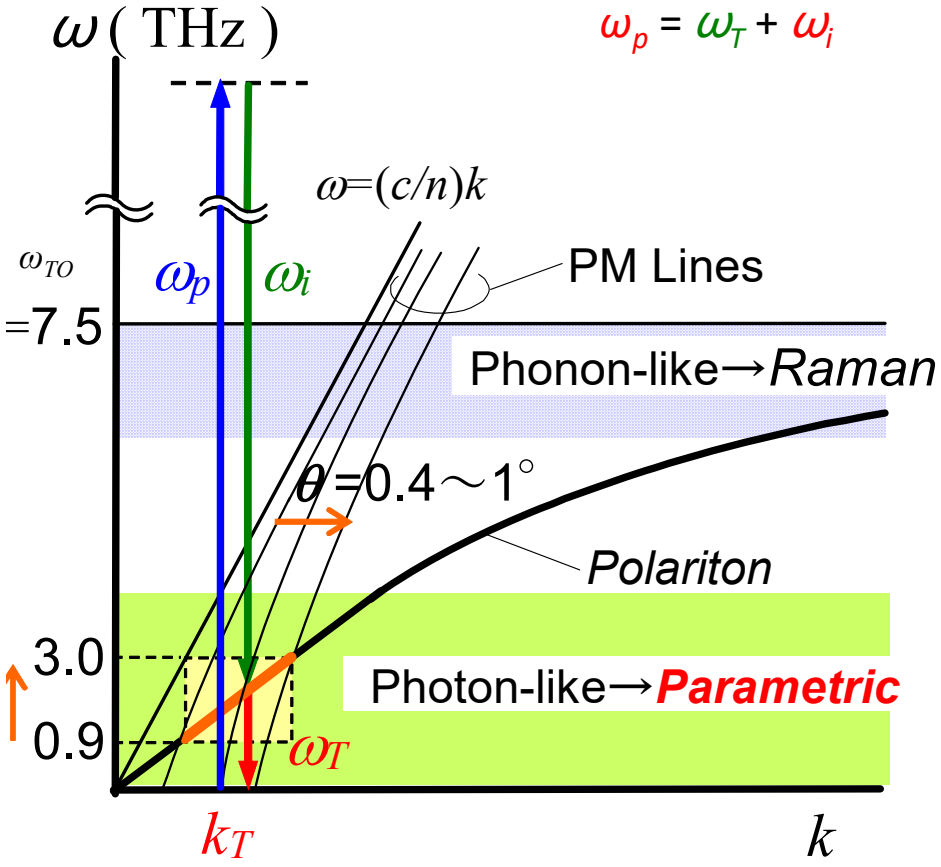
4. Summary

Injection-seeded Terahertz-wave parametric generation



Energy conservation law

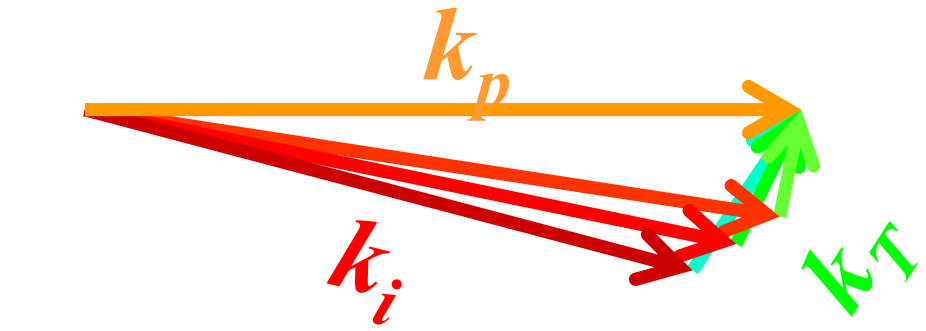
$\omega_p = \omega_T + \omega_i$

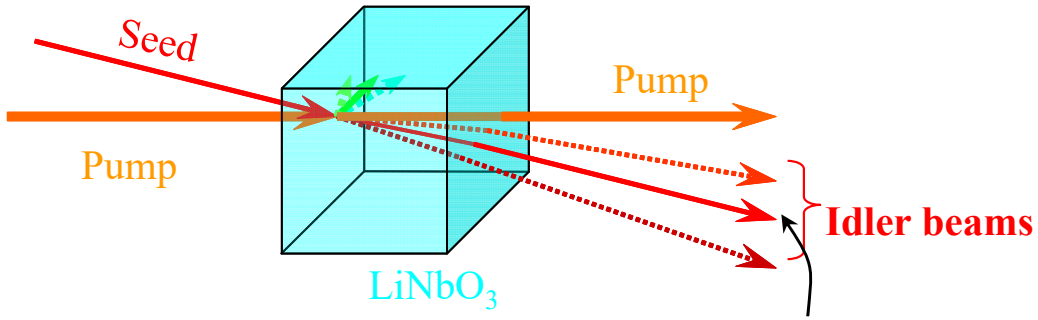


Dispersion curve of polariton

Phase-matching condition

$k_p = k_T + k_i$





Seeded idler beam

S. S. Sussman, *Stanford Univ., Microwave Lab. Rep. 1851*, (1970).

K. Kawase, J. Shikata, K. Imai, and H. Ito, "Transform-limited, narrow-linewidth, terahertz-wave parametric generator," *Applied Physics Letters,* vol. 78, pp. 2819-2821, 2001.

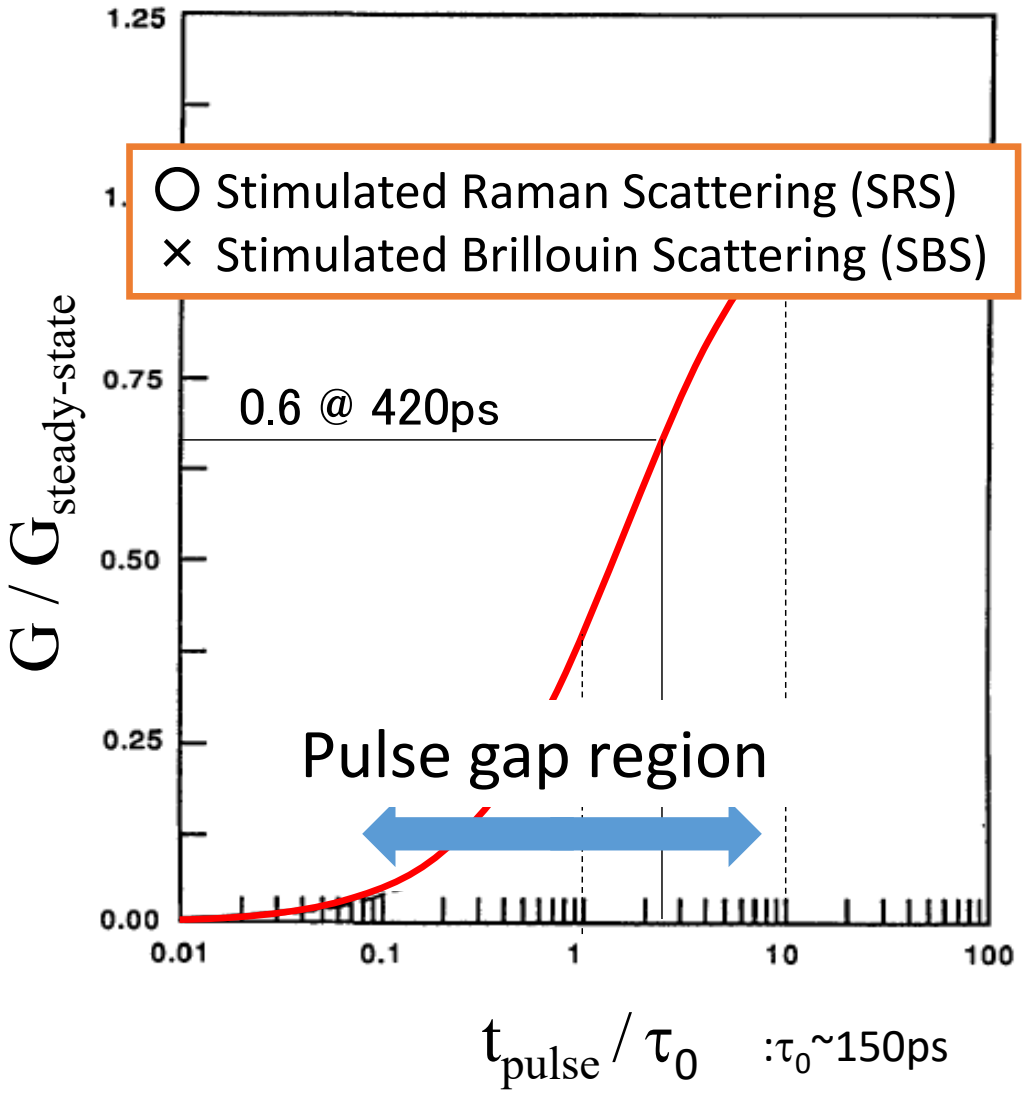
Gain of Stimulated Brillouin Scattering

SBS reduction is key factor for intense THz-wave generation

How long pulse duration is effective?

- Phonon lifetime of LN ~ 150 ps
- Steady state of SBS > 1.5 ns
- Shorter is better or not?
- Seems to be good around inflection point, 100 ~ 200 ps?

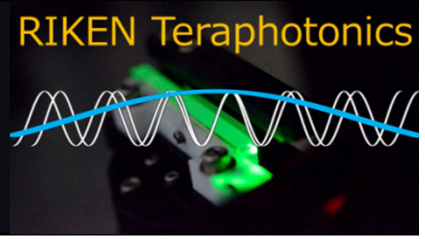
SBS gain as a function of pulse width



*A. de Bernabé, C. Prieto, and A. de Andrés, Journal of Applied Physics, **79**, 143–148 (1996).

G. W. Faris, L. E. Jusinski, and A. P. Hickman, J. Opt. Soc. Am. B, **10, 587–599 (1993).

Power spectra of the is-TPG



Max. output ~100 kW (peak)

Latest results

Pumping energy: 20 mJ/pulse
Seeding power: 800 mW

Five-order enhancement

Before this project

Max. output ~ 200 mW (peak)

Pumping energy: 45 mJ/pulse
Seeding power: 250 mW

Peak power of Terahertz-wave (W)

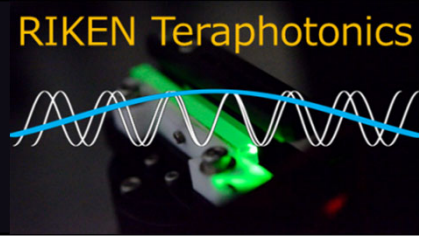
100 kW
10 kW
1 kW
100 W
10 W
1 W
100 mW
10 mW
1 mW

0.5
1
1.5
2
2.5
3

Frequency (THz)

H. Minamide et.al, J. Infrared, Millimeter, and Terahertz Waves **35**, 25 (2014).

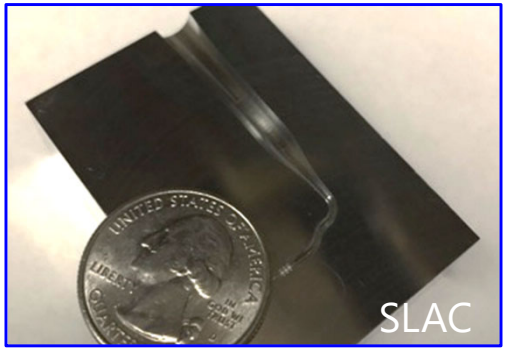
Application of intense THz-wave generation



Required THz-wave source

- 0.3 THz
- 1 MW
- 100 ps

→ ~GeV/m gradient



Current RF source

- ~3 GHz
- 10s MW
- ~μs

→ 30 MeV/m

L = cm ~ m

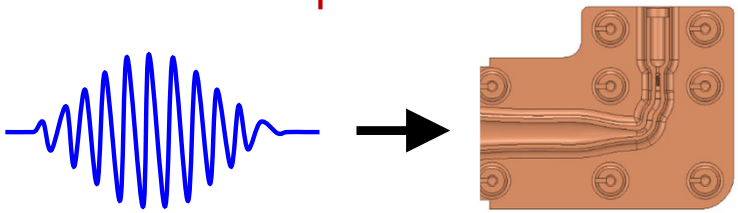
L=100 m ~ km

2 orders of magnitude higher gradients

➡ 100 times smaller electron accelerators is possible!!

■ Advantages of THz-wave electron accelerators

- Higher breakdown threshold ($\propto \omega^{1/2}$)
- Lower pulse energy: ($\propto \lambda^2$)
- Higher repetition rate: >1 kHz

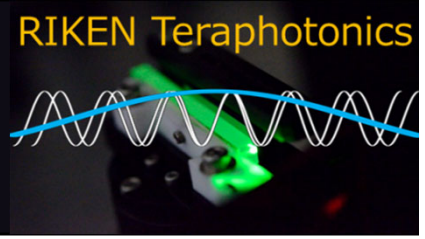


ω = 0.3 THz
P = 1 MW
τ = 100 ps

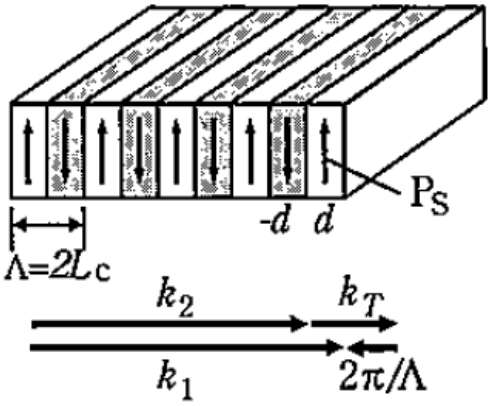
SLAC's accelerator structure
M. Othman *et al.*, APL **117**, 073502 (2020).

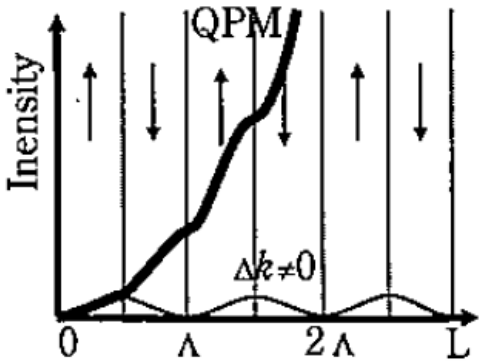
Characterization with KEK

Quasi-phase-matched (QPM) device Periodically-Poled Lithium Niobate (PPLN)



Phase-matching condition in PPLN can be controlled to the best at a wavelength user requires.





$$\Delta k = k_p - k_i - k_{THz} - k_\Lambda$$

$$I_3 = I_3(max)\frac{sin^2(\Delta kL/2)}{(\Delta kL/2)^2}$$

Reported experiment: PPGaAs: K. L. Vodopyanov, *CLEO2014,* STh4F.7.

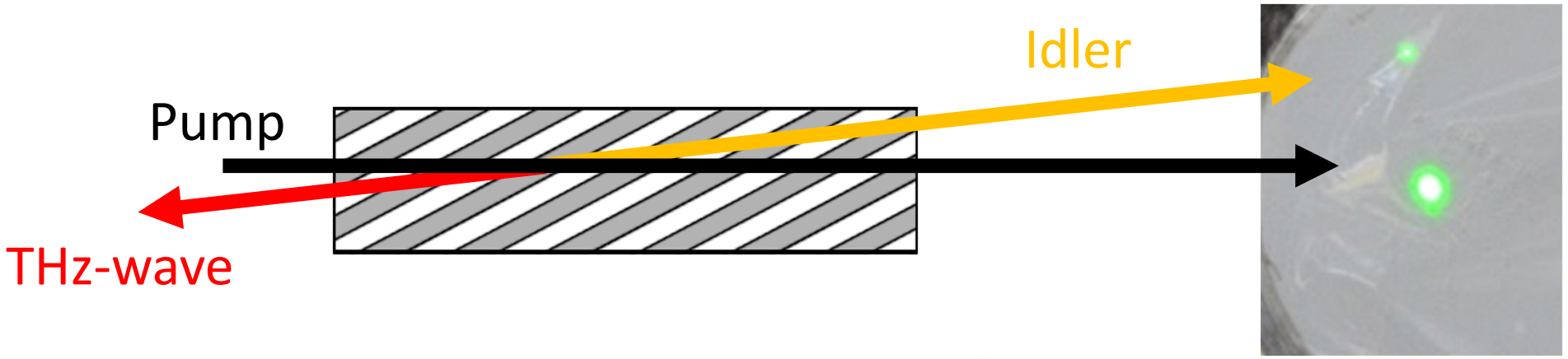
- C. Weiss, G. Torosyan, Y. Avetisyan, and R. Beigang, Opt. Lett. 26, 563-565 (2001).
- Y.-S. Lee, T. Meade, M. DeCamp, and T. B. Norris, Appl. Phys. Lett. 77, 1244 (2000).
- Y. Avetisyan, Y. Sasaki, and H. Ito, Appl Phys B 73, 511–514 (2001).

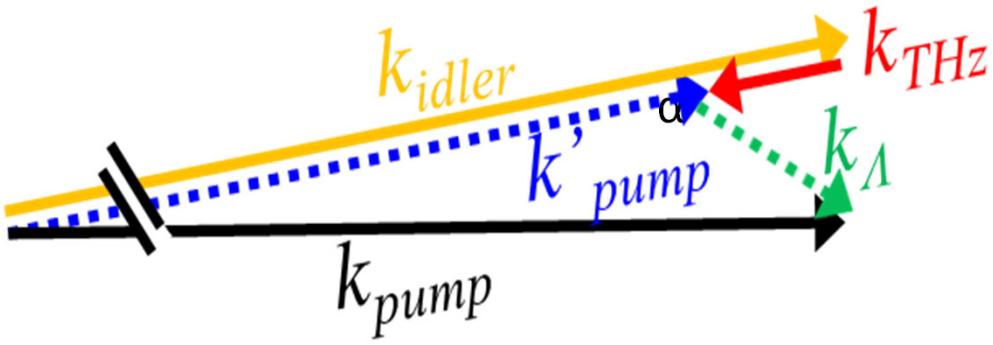
In phase mismatching Δk = 0, most efficient conversion is given.

Using PPLN, high conversion-efficiency is obtained because of well-optimization on its own artificial design. However, how seamless tunability would be obtained?

Nobel phase-matching condition

Discovery of new idler emission with different wavelength from that we expected in the experiment.

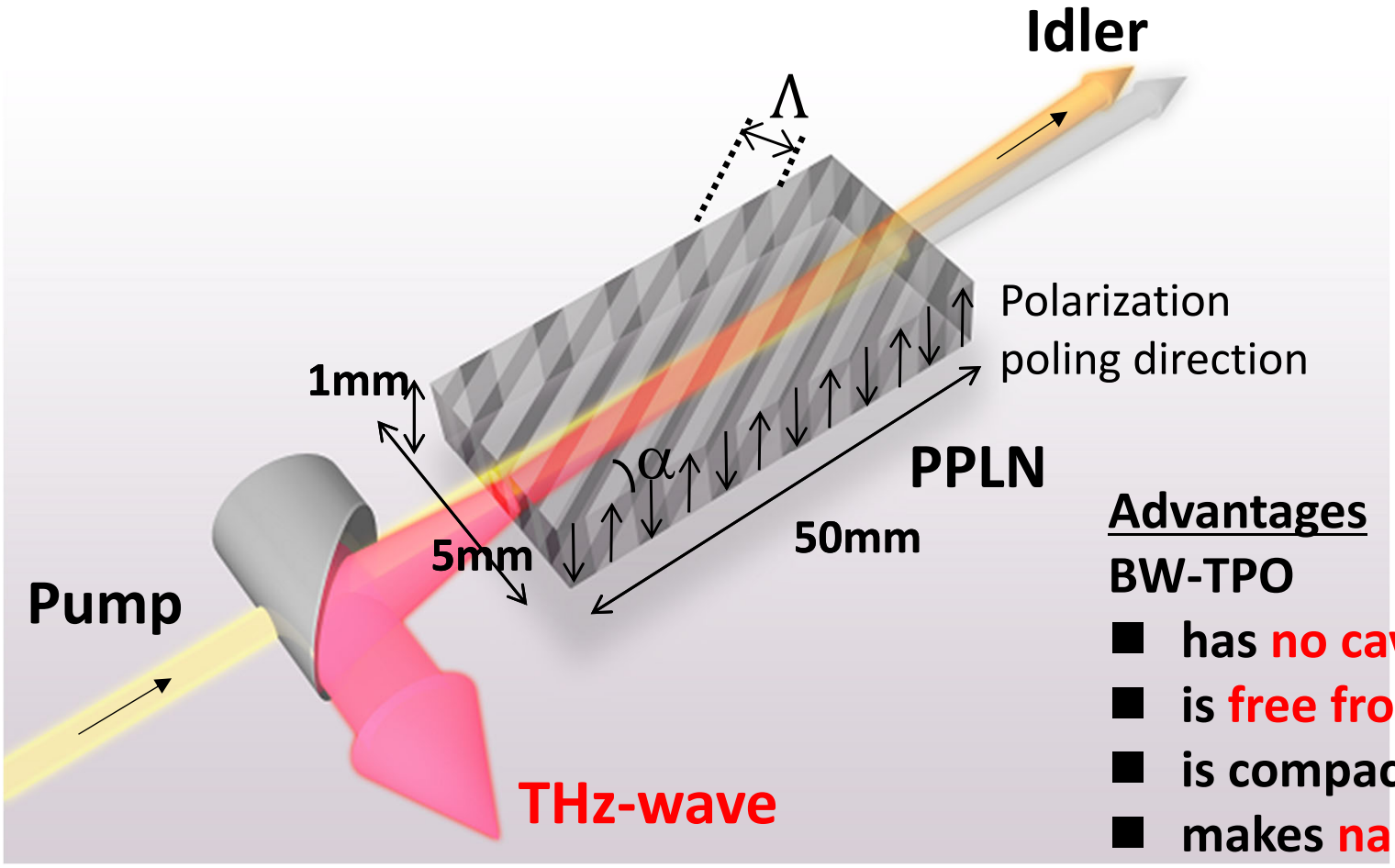




We proposed this new phase-matching condition from the experimental results.

Key: Collinear phase-matching + noncollinear phase-matching

Backward Terahertz-wave Parametric Oscillation (TPO)



Advantages

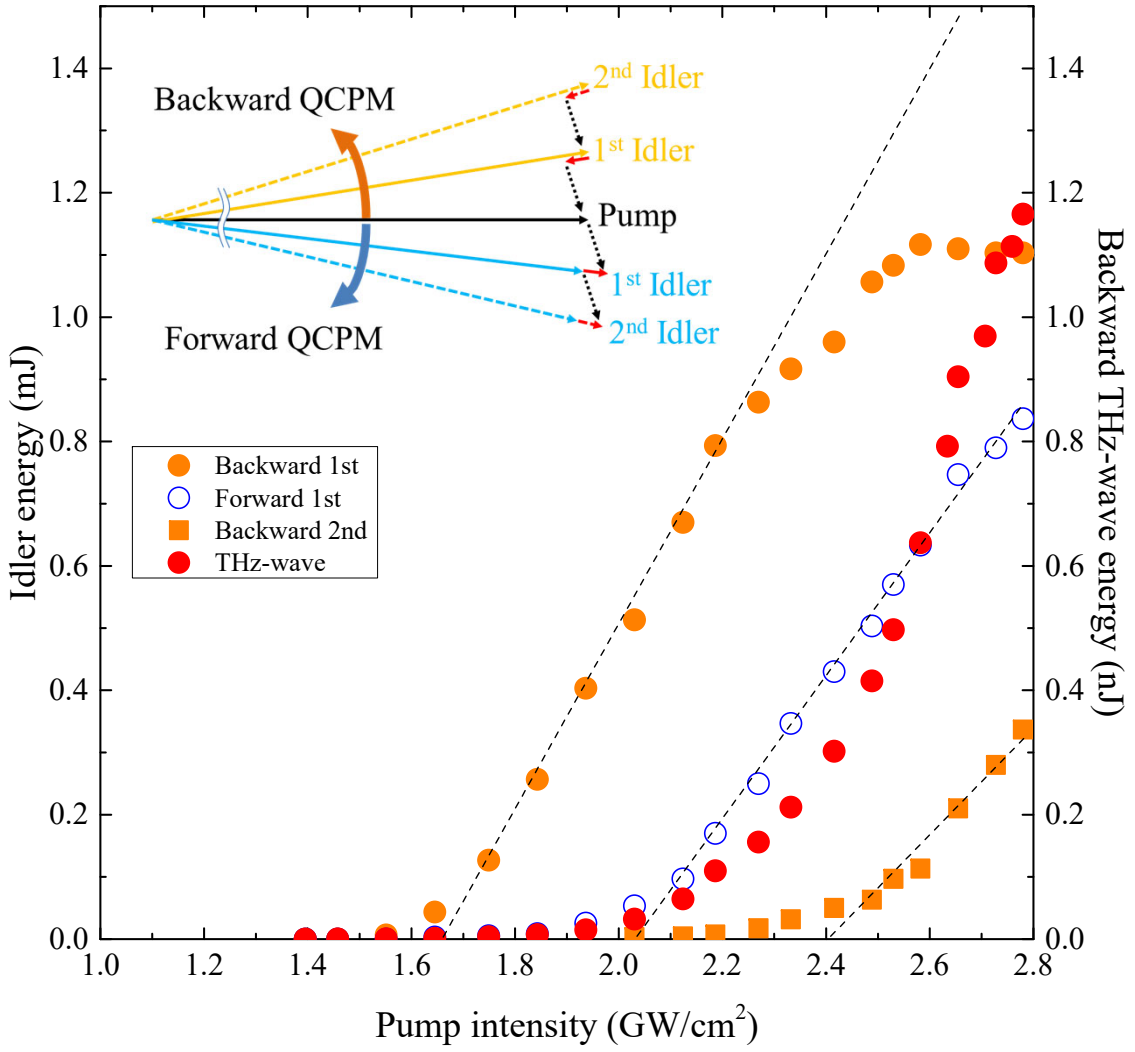
BW-TPO

- has no cavity mirrors.
- is free from arraignment of cavity.
- is compact and robust.
- makes narrowband THz-wave from a monochromatic NIR beam.
- with wide frequency tunability.
- has no back-conversion.
- has potential of perfect photon conversion.

K. Nawata et al., Sci Rep-Uk 9, 726 (2019).

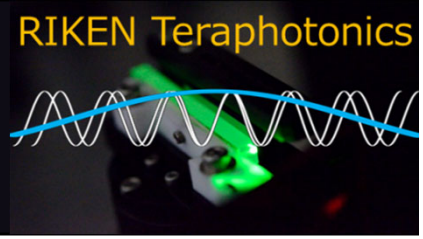
Patent: 2016-192374

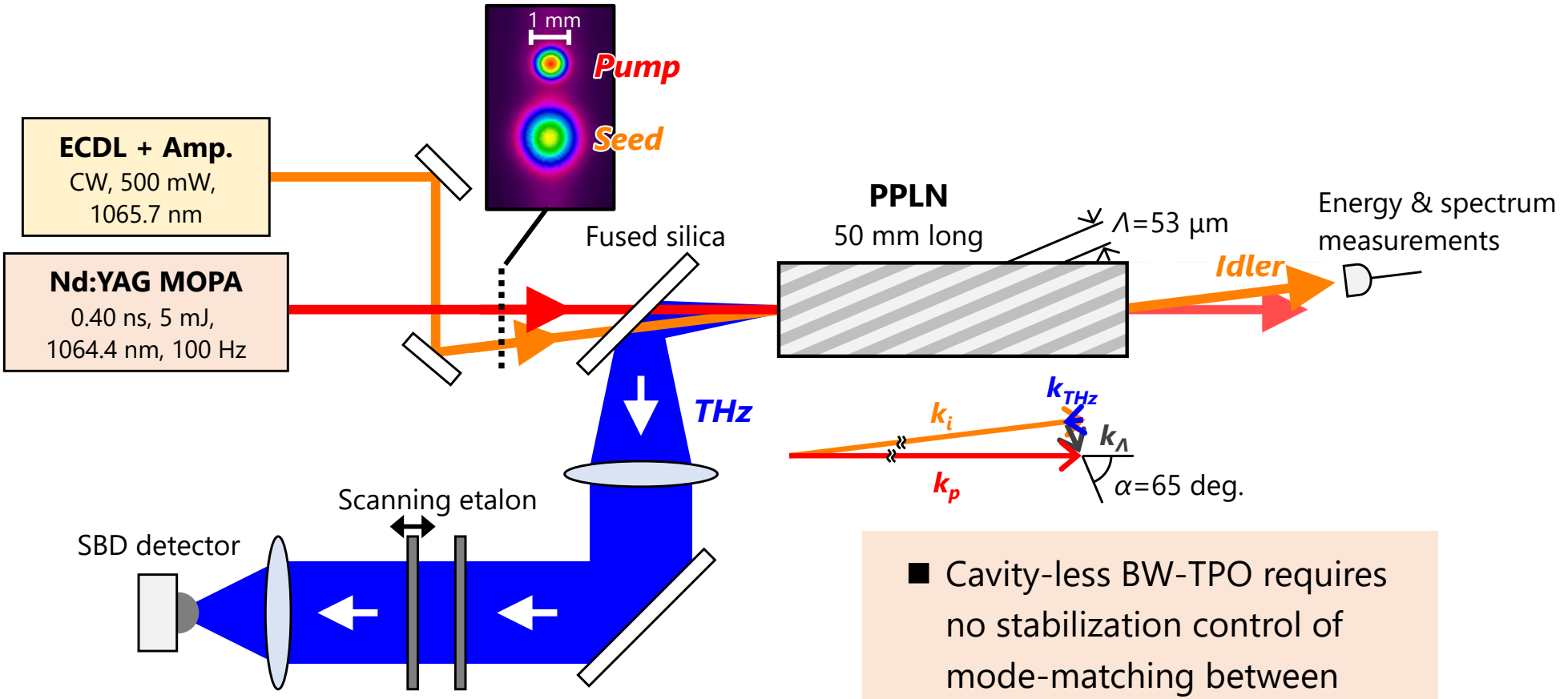
Output of BW-TPO



Efficient THz-wave generation was successfully obtained, so that not only BW oscillation but also FW generation were simultaneously generated in high pumping condition.

Experimental setup of Injection-seeded BW-TPO for idler beam

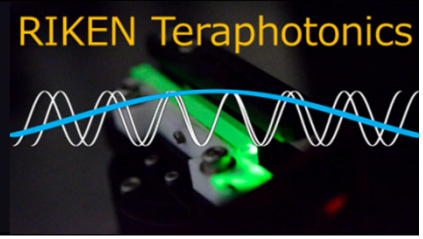


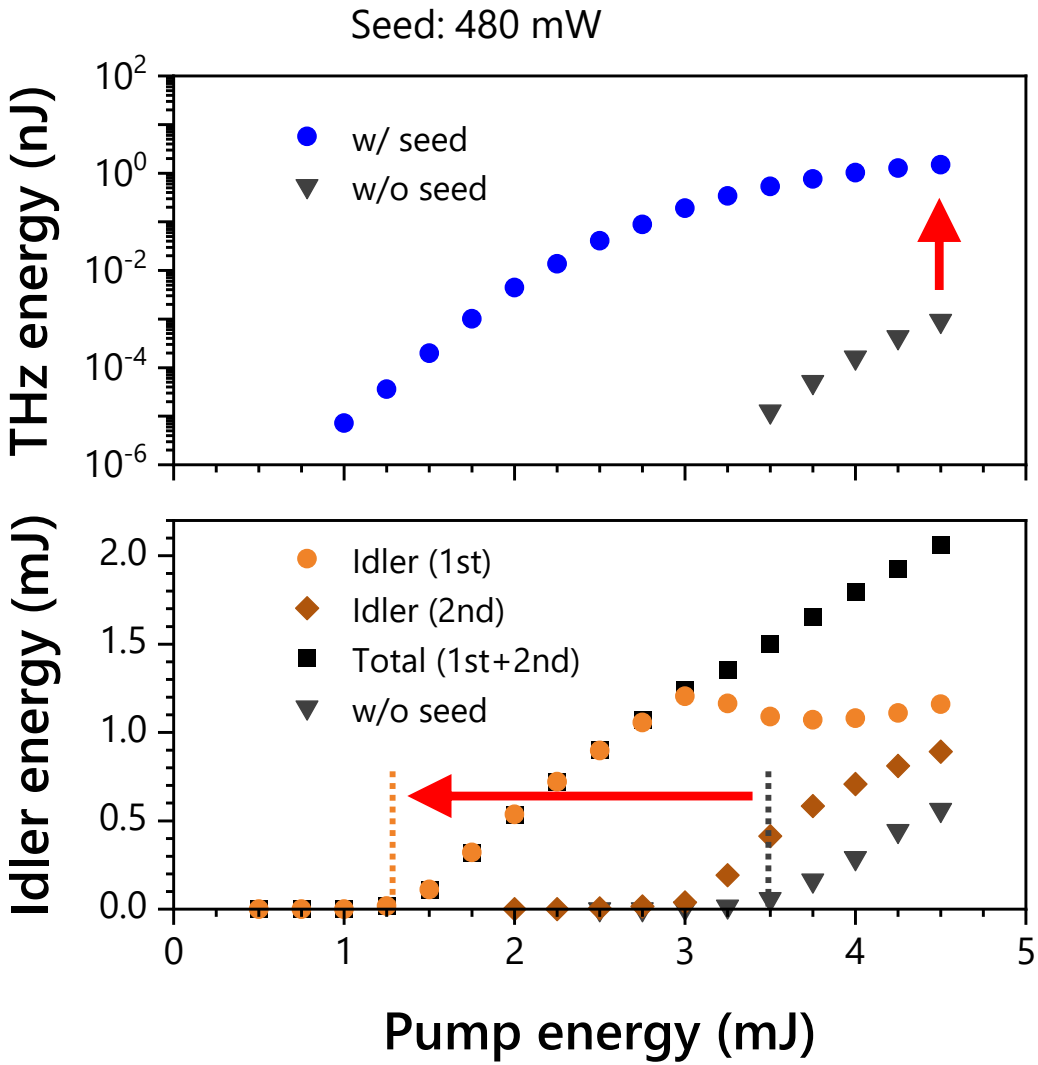


- Cavity-less BW-TPO requires no stabilization control of mode-matching between seed and oscillation modes

Injection seeding is best way to concentrate the large gain into one phase-matching condition dramatically.

Input-output characteristics | pump energy dependence





Backward THz-wave

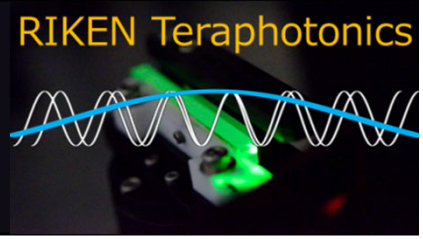
- Over 1000-fold enhancement
- Max. pulse energy: 1.2 nJ

Idler

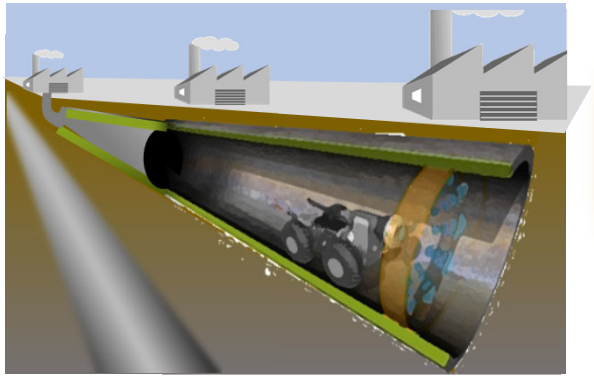
- Threshold reduction: 63%
- Total conversion efficiency: 47%

Efficient suppression for FW generation has been done.
Then, BW output required was selectively generated.

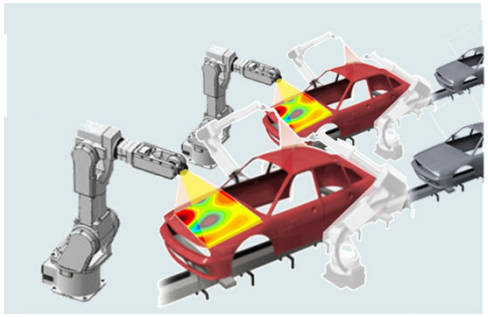
Ubiquitous remote sensing
2D and 3D imaging



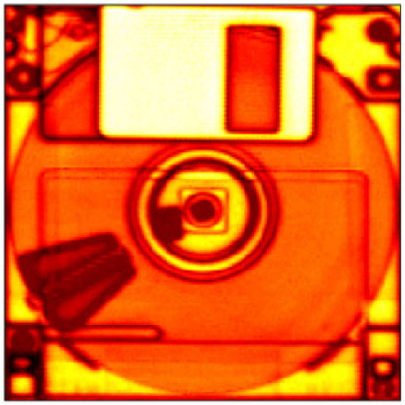
Infrastructure inspection
on autonomous robot

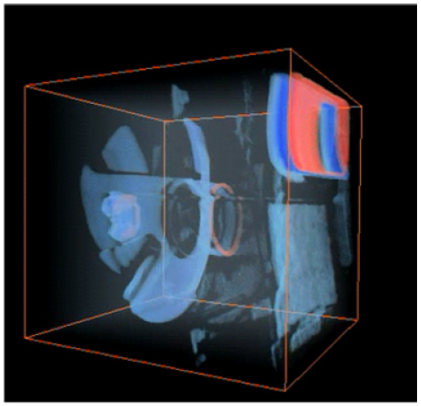


Industrial quality control
on robot arms

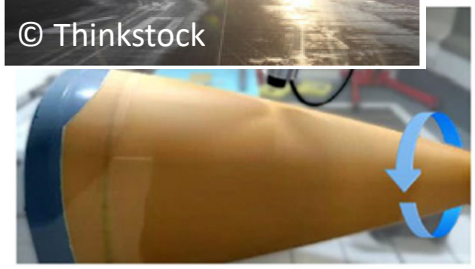


2D ➡ 3D





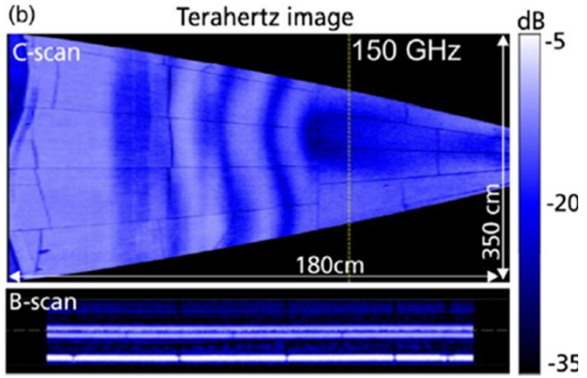
O.E. Vol. 20, No. 23 /pp. 25432, 2012



Rotating radome

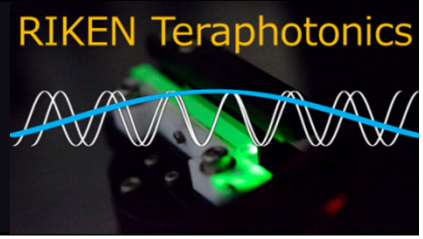
JIMT, 41, pp. 470–489, 2020

Radom inspection



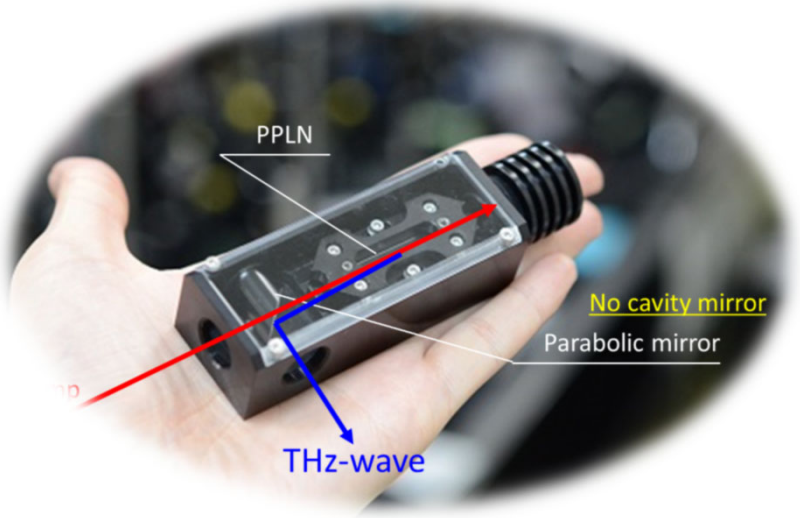
Volume inspection by BW-TPO would be applicable to NDT.

Summary



High-Brightness Backward TPO has been demonstrated

- ✓ **Injection-seeding provided stable emission and threshold reduction**
- ✓ **Cascaded process enhanced output THz-wave energy; 200W←80W**
- ✓ **Wide frequency tunability exceeding electric device source provides high-depth resolution**



The BW-TPO can be expected to open new uses in THz-wave driven particle acceleration or nondestructive testing.

Acknowledgment

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Industrial Collaborators:

MITSUBISHI ELECTRIC

MITSUBISHI HEAVY INDUSTRIES

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