テラヘルツ光源の現状

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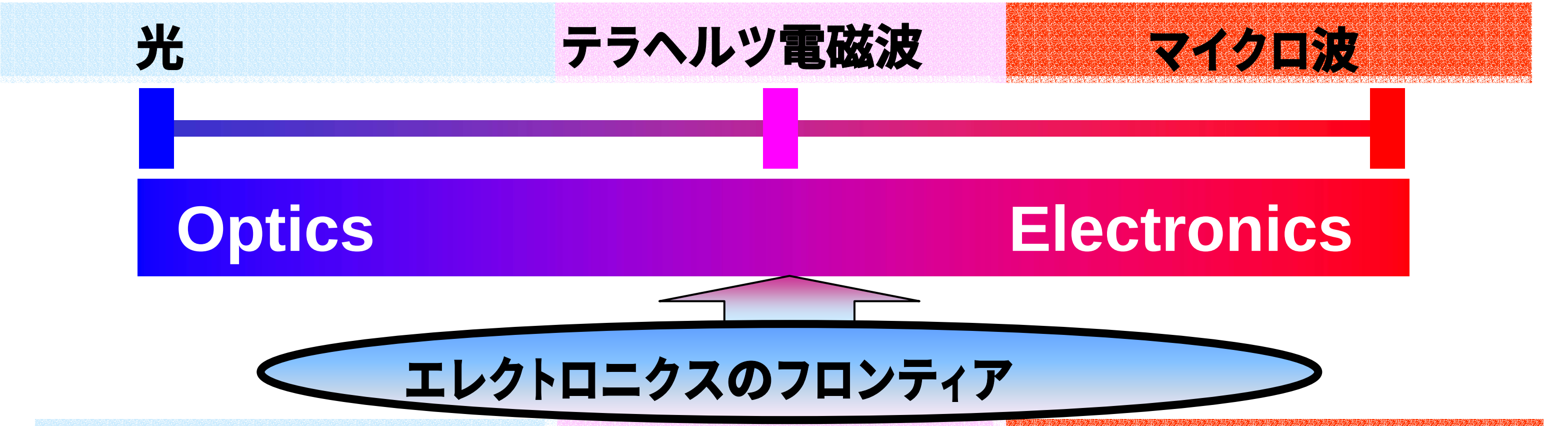
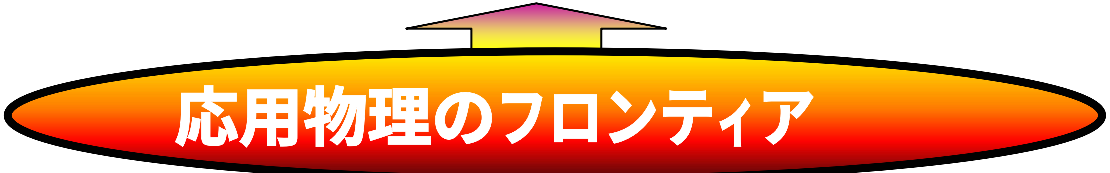
テラヘルツ電磁波とは？

テラヘルツ電磁波 = 遠赤外光 = サブミリ波



周波数	1 PHz (10^{15}Hz)	1 THz (10^{12}Hz)	1 GHz (10^{9}Hz)
波長	0.3 μm	300 μm	30 cm
周期	1 fs	1 ps	1 ns
ネルギー	4 eV	4 meV	4 μeV
	• Electronic-excitation state	• Phonon • Exciton • Cooper pair	• Laser-cooled atom



応用例;テラヘルツ電磁波による透視技術

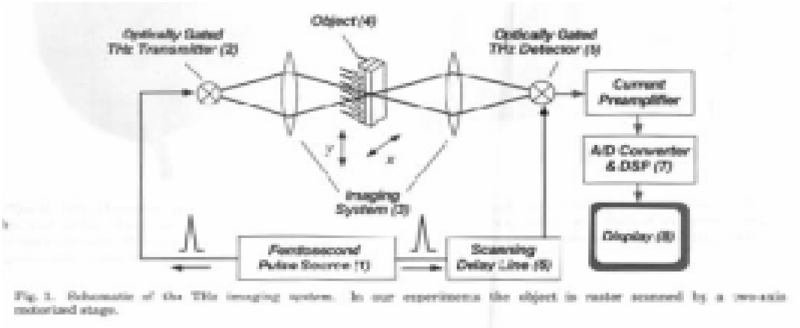
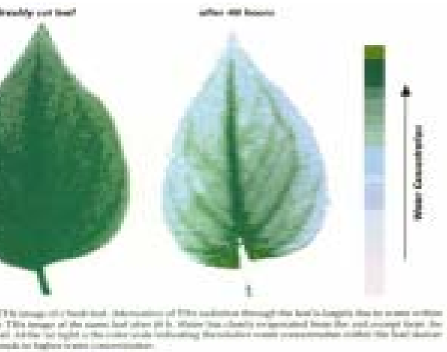
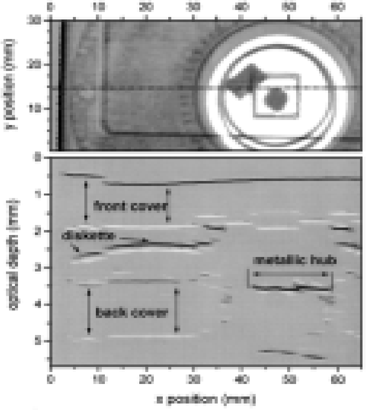


Fig. 1. Schematic of the THz imaging system. In our experiments the object is raster scanned by a two-axis motorized stage.

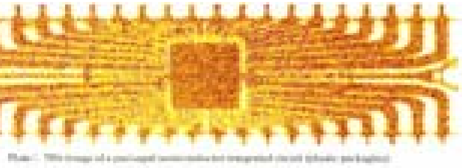
般的な検出システム ⟶ 長時間スキャンが必要



水分量計測



フロッピーディスクの
3次元透過画像計測



体集積回路の透過画像計測

@優れた透過特性
→エックス線とは異なった
安全な非破壊検査が可能

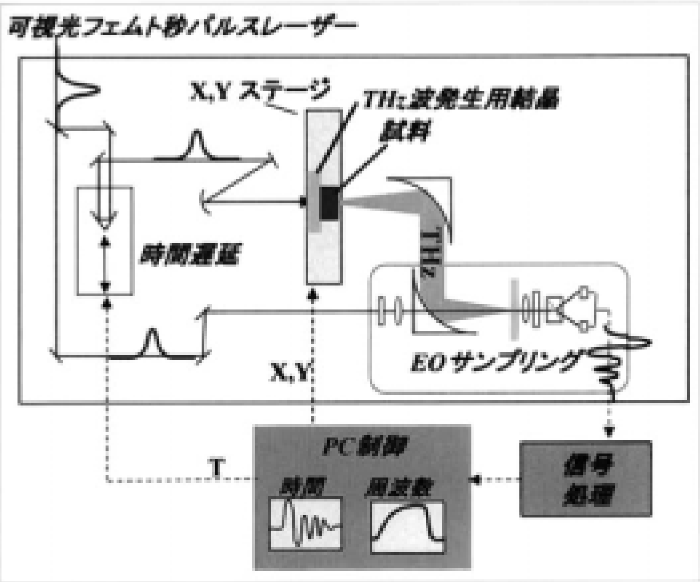
@遠赤外領域での超短パルス
(ピコ秒パルス)
→高時間分解能の測定が可能

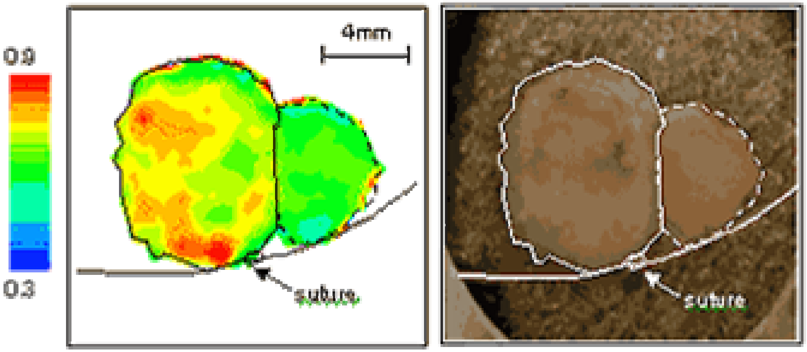
@水の吸収が強い領域
→水分に関する高感度測定が可

@新しいイメージングシステム
→様々な分野への応用が可能

OPTICS LETTERS 20, 1716 (19

応用例;テラヘルツ電磁波の生体応用

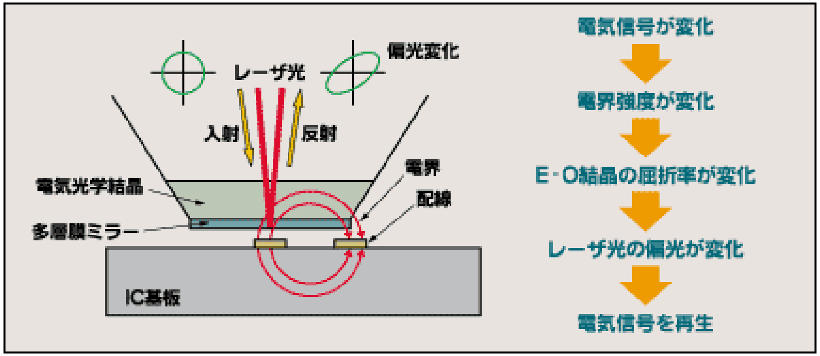




THz image

Visible Image

皮膚がんの腫瘍のイメージング



電気信号が変化

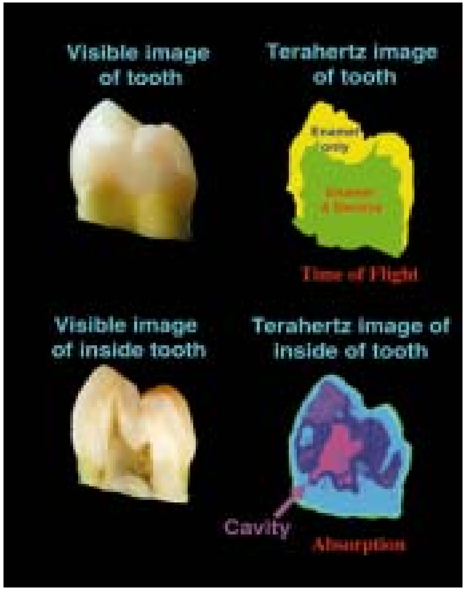
電界強度が変化

E･O結晶の屈折率が変化

レーザ光の偏光が変化

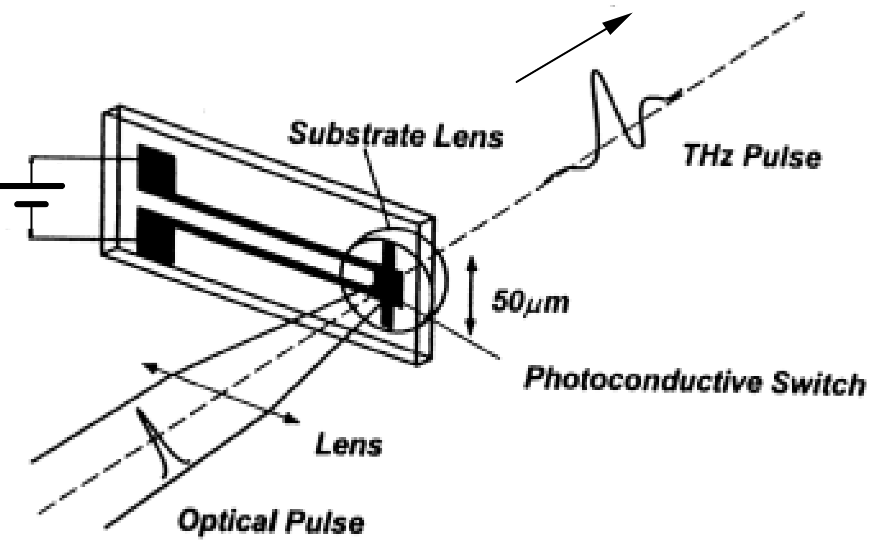
電気信号を再生

TOSHIBA Research Europe Limited



歯のイメージング

Photoconductive switch



Hz-radiation source & detector

@ D. H. Auston

APL vol. 43, 713 (1983)

+ Time domain spectroscop

+ high sensitivity for detect

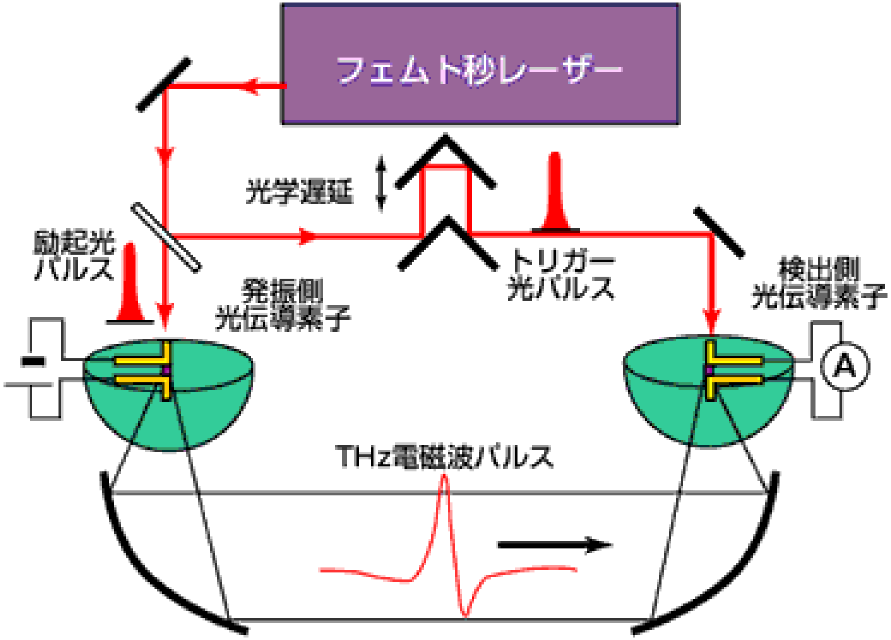
- Low THz-radiation power

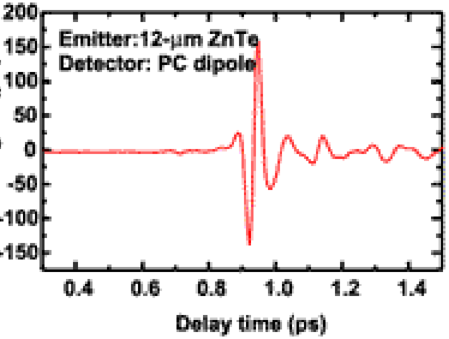
- Break down

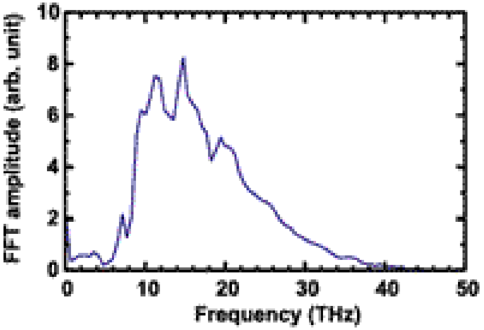
- Serious arraignment

Strong needs for high power
and simple THz-radiation sourc

光伝導スイッチによる時間分解分光法







CRLニュースより抜粋

- \+ 時間分解分光
- \+ 高感度検出
- \- 低出力
- \- ブレークダウンが起こりやす
- \- 調整が困難

様々なテラヘルツ電磁波発生法

・超短パルスレーザー励起による半導体素子からの発生法
　光伝導素子、半導体超格子、半導体表面など

D. H. Auston, Appl. Phys. Lett. 43, 713 (1983).

X. -C. Zhang, et al, Appl. Phys. Lett. 56, 1011 (1990).

・超電導電流の変調による発生法

M.Hangyo, et al, Appl. Phys. Lett. 69, 2122 (1996).

・光伝導素子を用いた差周波による発生法

K. A.McIntosh, et al, Appl. Phys. Lett. 67, 3844 (1995).

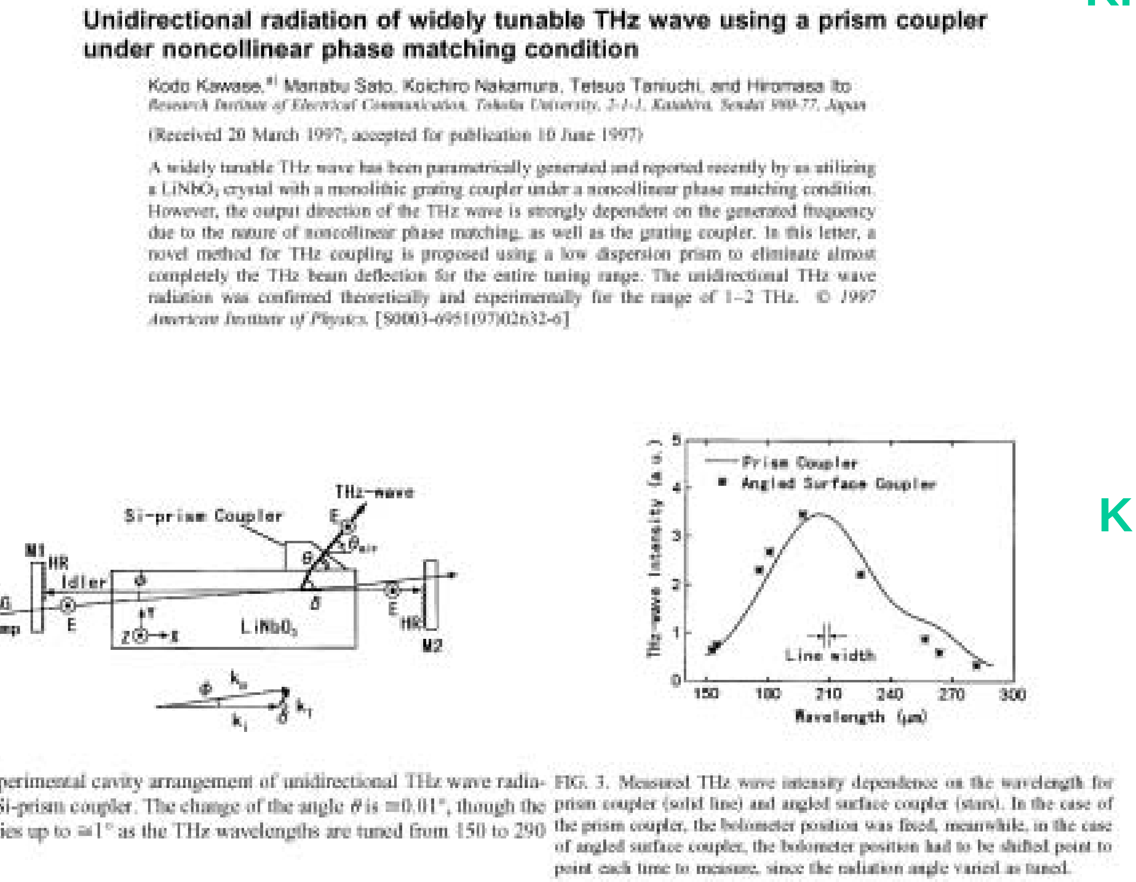
・非線形素子を用いたパラメトリック発振器による発生法

K. Kawase, et al, Appl. Phys. Lett. 68, 559 (1995).

・電流注入による半導体素子からのテラヘルツ電磁波発生法

R. Kohler, et al, Nature 417, 156 (2002).

テラヘルツパラメトリック発振



Unidirectional radiation of widely tunable THz wave using a prism coupler under noncollinear phase matching condition

Kodo Kawase,[a] Manabu Sato, Koichiro Nakamura, Tetsuo Taniuchi, and Hiromasa Ito
Research Institute of Electrical Communication, Tohoku University, 2-1-1, Katahira, Sendai 980-77, Japan

(Received 20 March 1997; accepted for publication 10 June 1997)

A widely tunable THz wave has been parametrically generated and reported recently by us utilizing a $LiNbO_3$ crystal with a monolithic grating coupler under a noncollinear phase matching condition. However, the output direction of the THz wave is strongly dependent on the generated frequency due to the nature of noncollinear phase matching, as well as the grating coupler. In this letter, a novel method for THz coupling is proposed using a low dispersion prism to eliminate almost completely the THz beam deflection for the entire tuning range. The unidirectional THz wave radiation was confirmed theoretically and experimentally for the range of 1–2 THz. © 1997 *American Institute of Physics.* [S0003-6951(97)02632-6]

perimental cavity arrangement of unidirectional THz wave radia- Si-prism coupler. The change of the angle θ is ≅0.01°, though the ies up to ≅1° as the THz wavelengths are tuned from 150 to 290

FIG. 3. Measured THz wave intensity dependence on the wavelength for prism coupler (solid line) and angled surface coupler (stars). In the case of the prism coupler, the bolometer position was fixed, meanwhile, in the case of angled surface coupler, the bolometer position had to be shifted point to point each time to measure, since the radiation angle varied as tuned.

K. Kawase et al, APL, 71, 753 (19

+ 波長可変 (1~2THz)

+ シリコンプリズムカップラーによる取り出し効率の高効率化

K. Kawase et al, APL, 80, 195 (2

+ 200mW以上の出力

+ 100MHz以下の狭帯域

Terahertz semiconductor-heterostructure lase

Terahertz semiconductor-heterostructure laser

Rüdeger Köhler*, Alessandro Tredicucci*, Fabio Beltram*,
Harvey E. Beere†, Edmund H. Linfield†, A. Giles Davies†,
David A. Ritchie†, Rita C. Iotti‡ & Fausto Rossi‡

* *NEST-INFM and Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126 Pisa, Italy*
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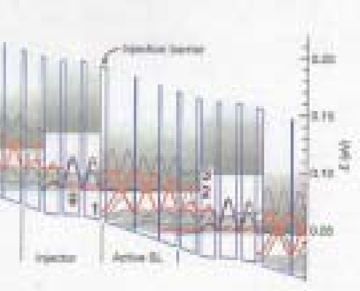
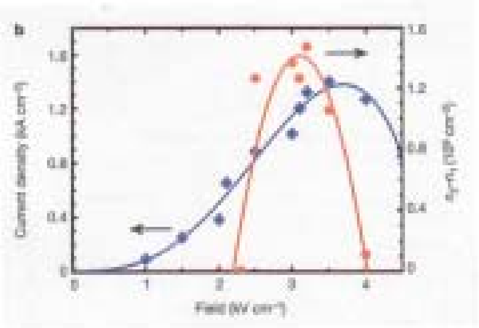
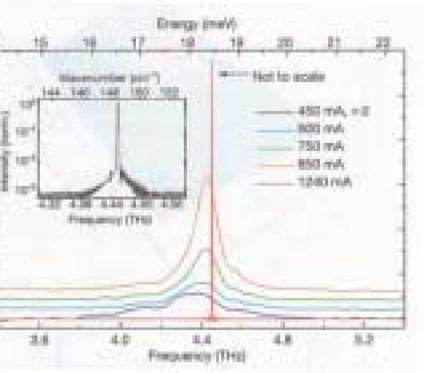
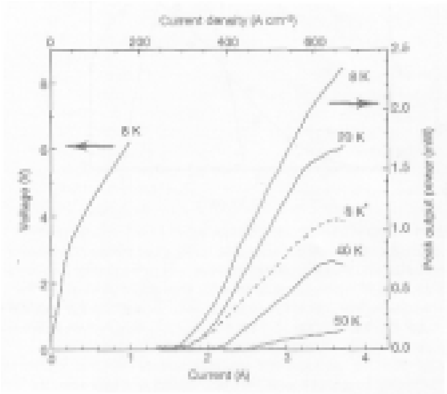
‡ *INFM and Dipartimento di Fisica, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*

**R. Köhler et al,
Nature, 417, 156 (2002)**









**+ First semiconductor lase
in THz region**

**+ More than 2-mW output
power at 4.4 THz**

- Under 50K

高温超電導体薄膜からのテラヘルツ電磁波発生

Terahertz radiation from superconducting $YBa_2Cu_3O_{7-\delta}$ thin films excited by femtosecond optical pulses

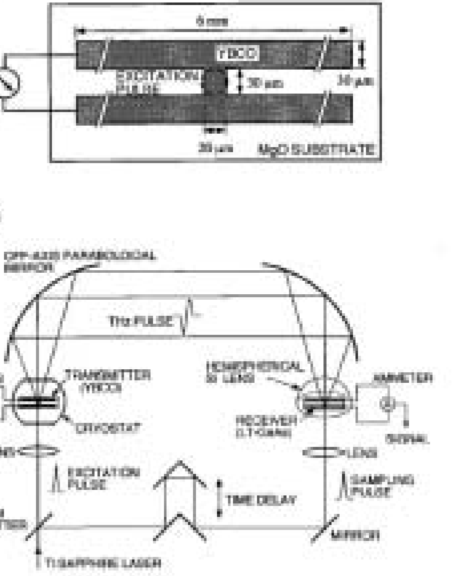
M. Hangyo,[a] S. Tomozawa, and Y. Murakami

M. Tonouchi, M. Tani, Z. Wang, and K. Sakai

S. Nakashima

(Received 23 February 1996; accepted for publication 23 July 1996)

Ultrashort electromagnetic waves (600 fs width) from superconducting YBCO thin films have been observed by irradiating current-biased samples with femtosecond optical laser pulses (80 fs width). The Fourier component of the pulse extends up to ~2 THz. The characteristics of the radiation are studied and the radiation mechanism is ascribed to the ultrafast supercurrent modulation by the laser pulses, which induce the nonequilibrium superconductivity. © 1996 American Institute of Physics. [S0003-6951(96)04840-1]



) Schematic structure of the sample. (b) Experimental setup of the
tion and detection system.

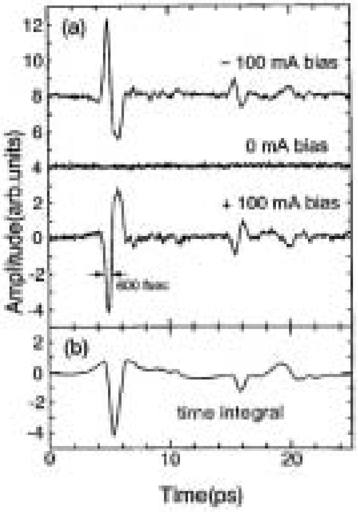


FIG. 2. (a) Measured electrical pulse of the freely propagating THz radiation for various bias currents. (b) Time integral of the electrical pulse for the bias current of + 100 mA.

@ 超伝導電流の変調に
るテラヘルツ電磁波発生

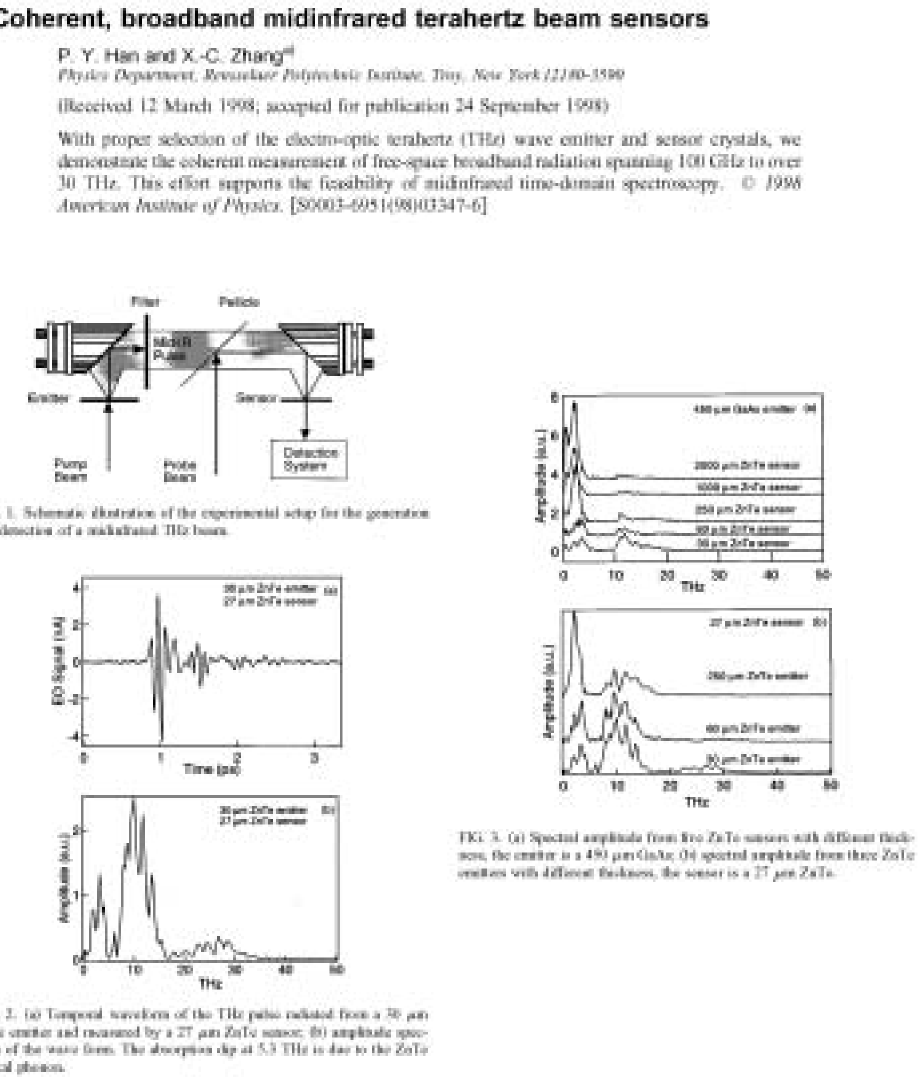
@ 超伝導電流のマッピン
が可能

@ 600fsのパルス幅

@ 2THzに及ぶスペクト

M. Hangyo et al,
APL, 69, 2122 (1996)

光整流による広帯域テラヘルツ電磁波発生



Coherent, broadband midinfrared terahertz beam sensors

P. Y. Han and X.-C. Zhang[a]
Physics Department, Rensselaer Polytechnic Institute, Troy, New York 12180-3590

(Received 12 March 1998; accepted for publication 24 September 1998)

With proper selection of the electro-optic terahertz (THz) wave emitter and sensor crystals, we demonstrate the coherent measurement of free-space broadband radiation spanning 100 GHz to over 30 THz. This effort supports the feasibility of midinfrared time-domain spectroscopy. © *1998 American Institute of Physics.* [S0003-6951(98)03547-6]

. 1. Schematic illustration of the experimental setup for the generation
detection of a midinfrared THz beam.

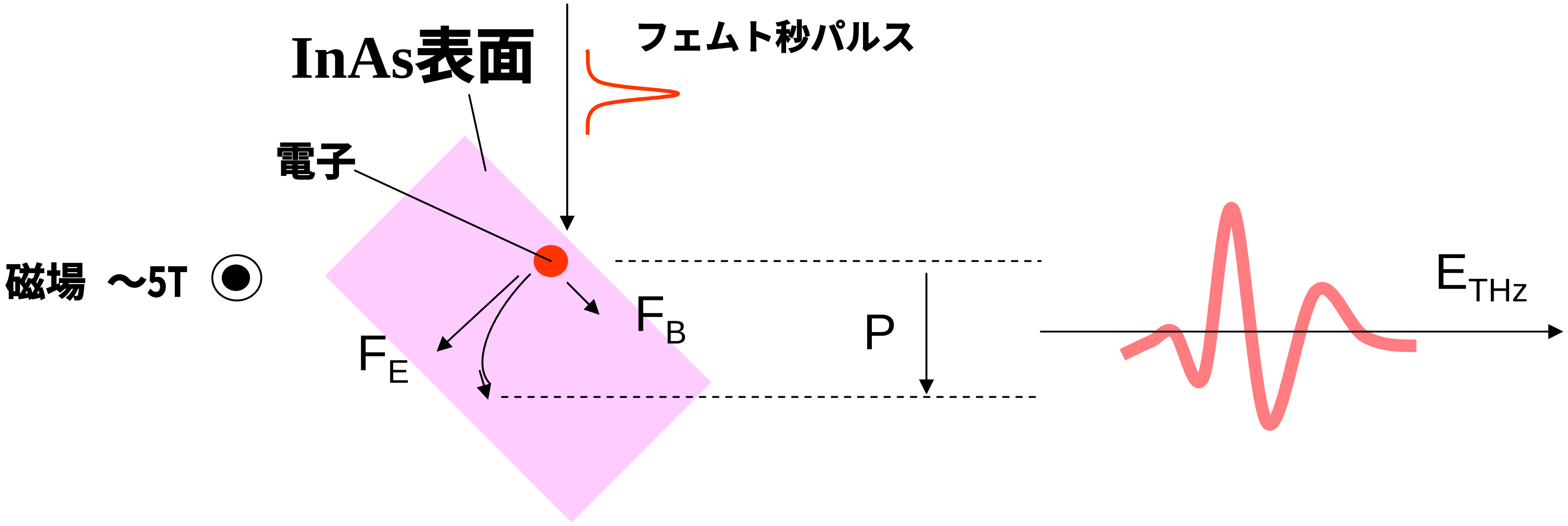
2. (a) Temporal waveform of the THz pulse radiated from a 30 μm
emitter and measured by a 27 μm ZnTe sensor; (b) amplitude spec-
of the wave form. The absorption dip at 5.3 THz is due to the ZnTe
al phonon.

FIG. 3. (a) Spectral amplitude from five ZnTe sensors with different thickness, the emitter is a 490 μm GaAs; (b) spectral amplitude from three ZnTe emitters with different thickness, the sensor is a 27 μm ZnTe.

ZnTeやGaAsからの100GHzから30THzに及ぶ広帯域THz電磁波発生

P. Y. Han et al,
APL, 73, 3049 (1998)

テラヘルツ電磁波の発生原理



$$(t) \propto \frac{\partial v}{\partial t} \propto \frac{\partial^2 p}{\partial t^2} \propto -\frac{e}{m_e}(E_{suf} + v \times B)$$

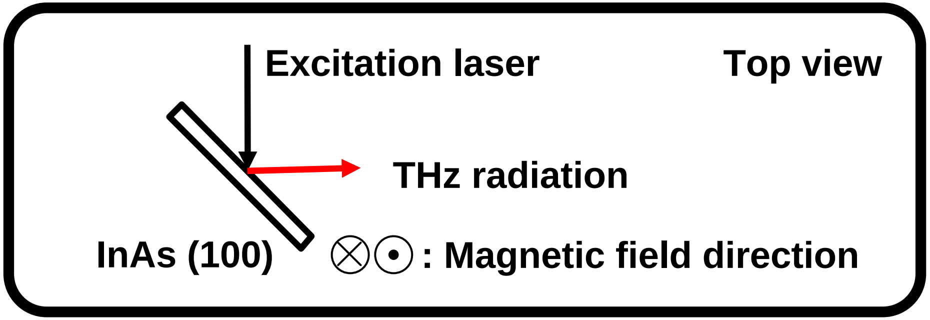
$$THz = E_{THz}^2 \propto \left(\frac{\partial \vec{J}}{\partial t}\right)^2 = \left(nea(t)\right)^2$$

電子の有効質量

GaAs		InAs
$0.063m_0$	>	0.024

$m_0 = 9.10 \times 10^{-31}$ (k

Time-Domain Measurement



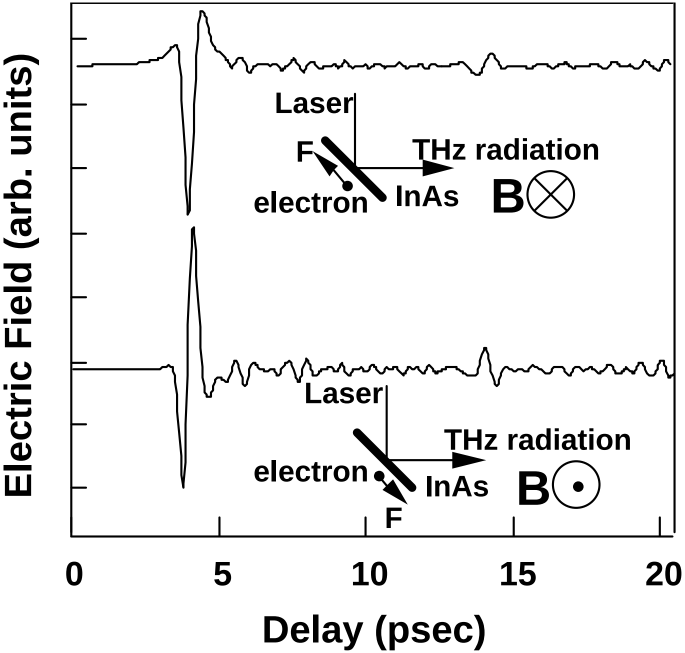
Excitation laser

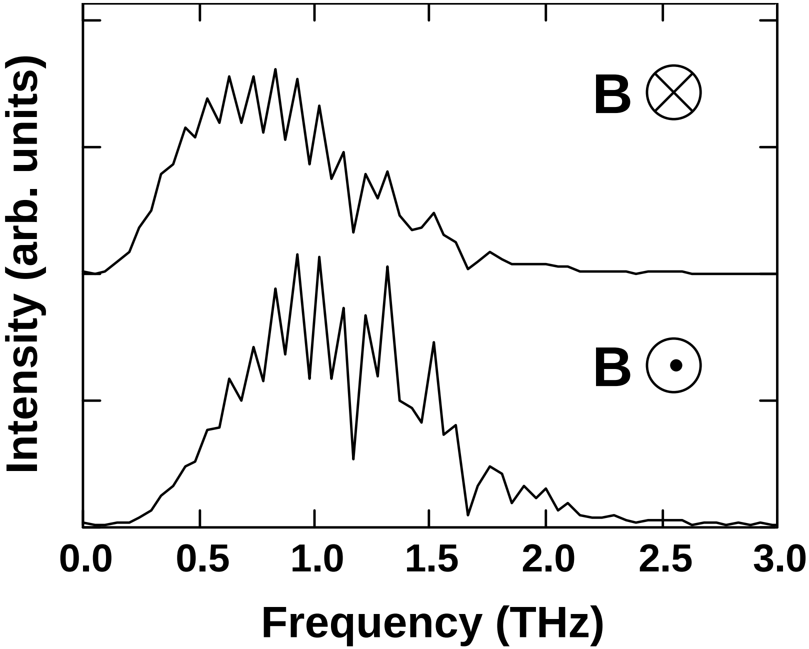
Top view

THz radiation

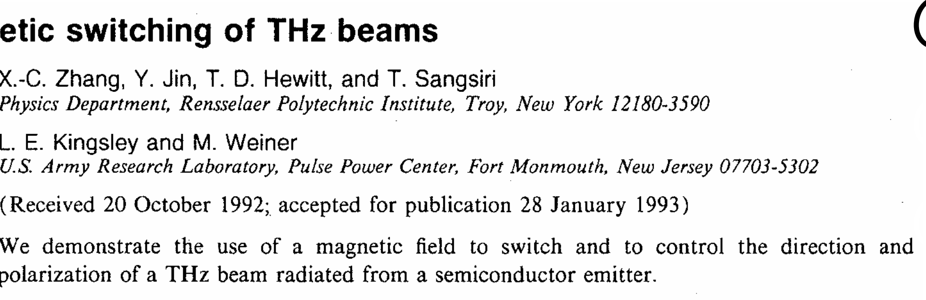
InAs (100)

⊗⊙ : Magnetic field direction





Basic magnetic field enhancement scheme of THz radiation

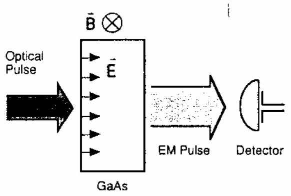


etic switching of THz beams

X.-C. Zhang, Y. Jin, T. D. Hewitt, and T. Sangsiri
Physics Department, Rensselaer Polytechnic Institute, Troy, New York 12180-3590
L. E. Kingsley and M. Weiner
U.S. Army Research Laboratory, Pulse Power Center, Fort Monmouth, New Jersey 07703-5302

(Received 20 October 1992; accepted for publication 28 January 1993)

We demonstrate the use of a magnetic field to switch and to control the direction and polarization of a THz beam radiated from a semiconductor emitter.



The top view of the experimental configuration for the magnetic
f a THz beam.

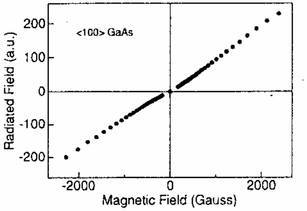


FIG. 3. The peak value of terahertz radiation vs the strength of the external magnetic field.

$$\boldsymbol{a} = \frac{d\mathbf{v}}{dt} = -\frac{e}{m_e^*}\left(\boldsymbol{E} + \mathbf{v} \times \boldsymbol{B}\right)$$

@ Prof. X. -C. Zhang group

Univ. of Rensselaer

APL. 62, 2003 (1993)

+ Quadratic magnetic field dependence of THz radiatio

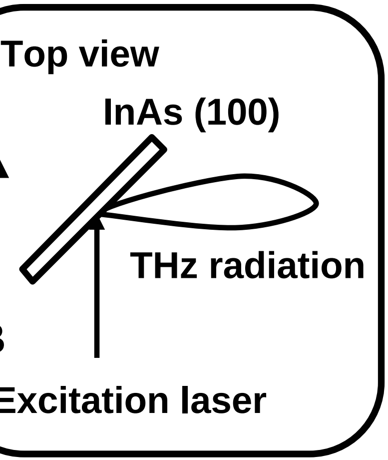
– GaAs with large electron ma

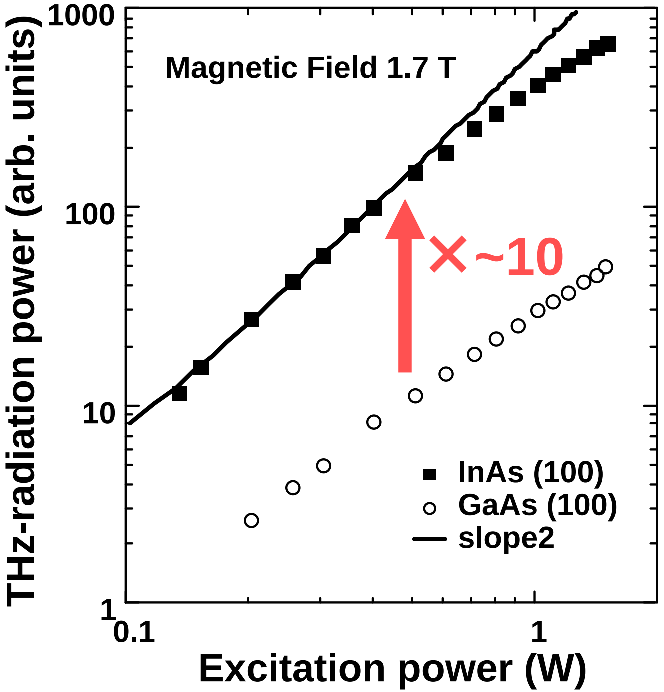
– Low magnetic field

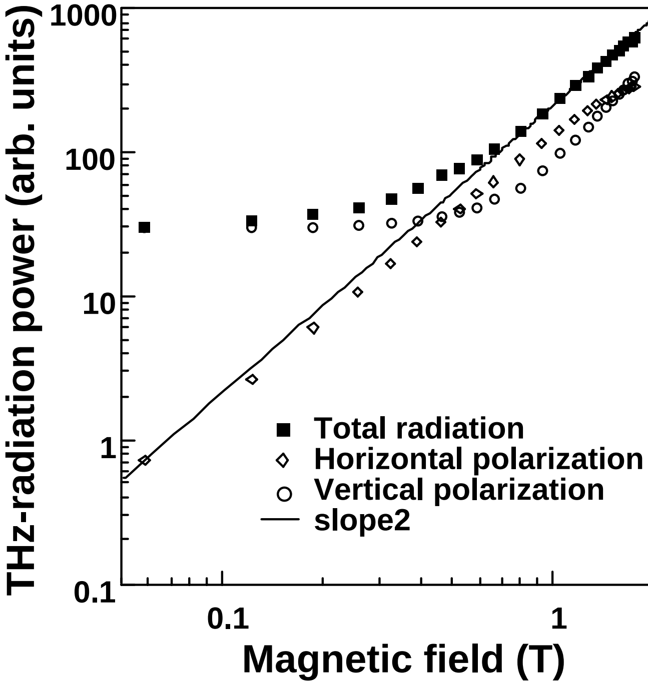
– Low excitation power

agnetic field enhancement scheme was found by X. -C. Zhar

agnetic field and excitation power dependenc of THz-radiation power







- The THz-radiation power from InAs is one order larger thar that from GaAs. (1/3 m_{eGaAs} ~ m_{eInAs})
- THz-radiation power shows quadratic magnetic field and excitation power dependence.

JAP 84, 654 (1998)

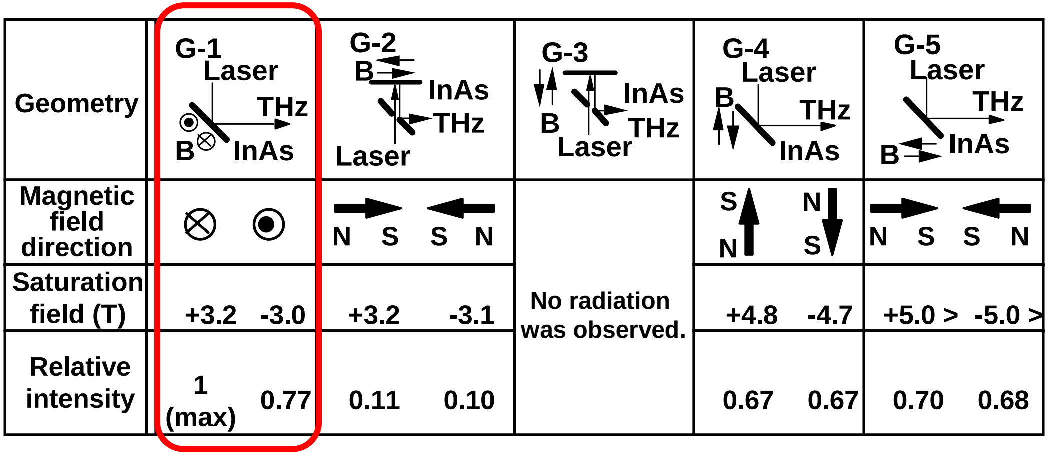
High magnetic field experiment in different geometry

aturation of THz-radiation power from femtosecond-laser-irradiated As in a high magnetic field

Hideyuki Ohtake,[a] Shingo Ono,[b] Masahiro Sakai, Zhenlin Liu, Takeyo Tsukamoto,[b] and Nobuhiko Sarukura[c]
Institute for Molecular Science (IMS), Myodaiji, Okazaki 444-8585, Japan

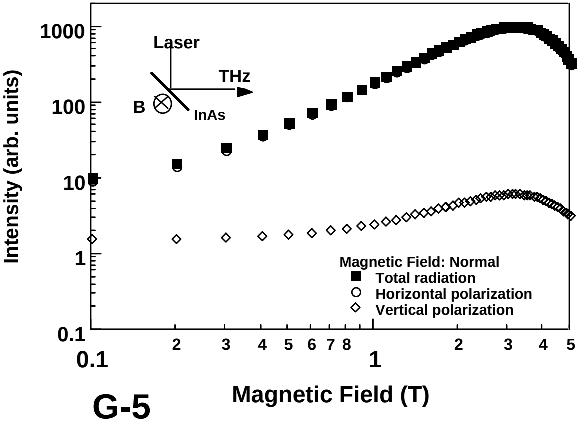
(Received 13 December 1999; accepted for publication 19 January 2000)

THz-radiation power from femtosecond-pulse-irradiated InAs is found to be saturated at the magnetic field around 3 T. Additionally, we find that this saturation magnetic field strongly depends on geometrical layout. Interesting magnetic-field dependence of the center frequency for THz radiation is also observed. © *2000 American Institute of Physics.* [S0003-6951(00)03311-8]

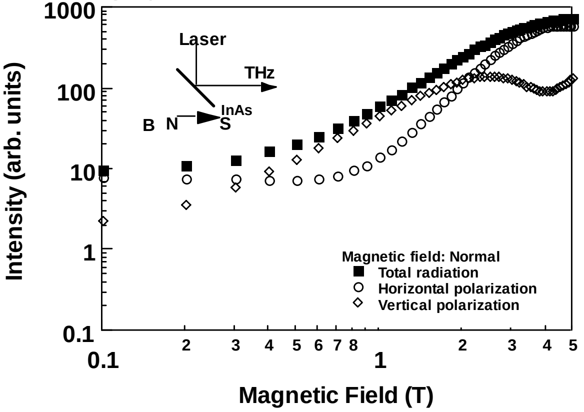


Geometry	G-1 Laser THz B ⊙ ⊗ InAs	G-2 B InAs THz Laser	G-3 B InAs THz Laser	G-4 Laser B THz InAs	G-5 Laser THz B InAs
Magnetic field direction	⊗ ⊙	→ N S ← S N	No radiation was observed.	S ↑ N N ↓ S	→ N S ← S N
Saturation field (T)	+3.2 -3.0	+3.2 -3.1		+4.8 -4.7	+5.0 > -5.0 >
Relative intensity	1 (max) 0.77	0.11 0.10		0.67 0.67	0.70 0.68

G-1

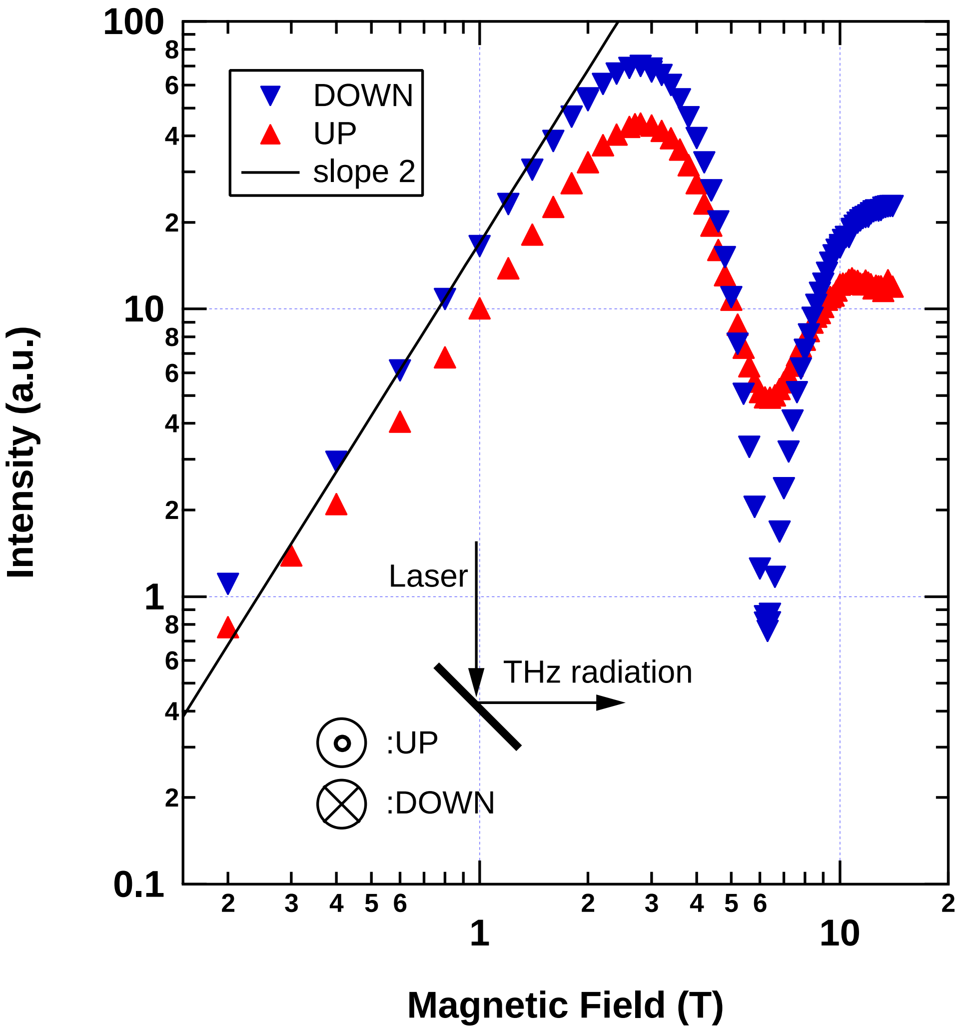


G-5



Clear saturation is observed at around 3-T magnetic field in he case of the G-1 geometrical layout. APL 76, 1398 (2000)

Magnetic field dependence of THz-radiation



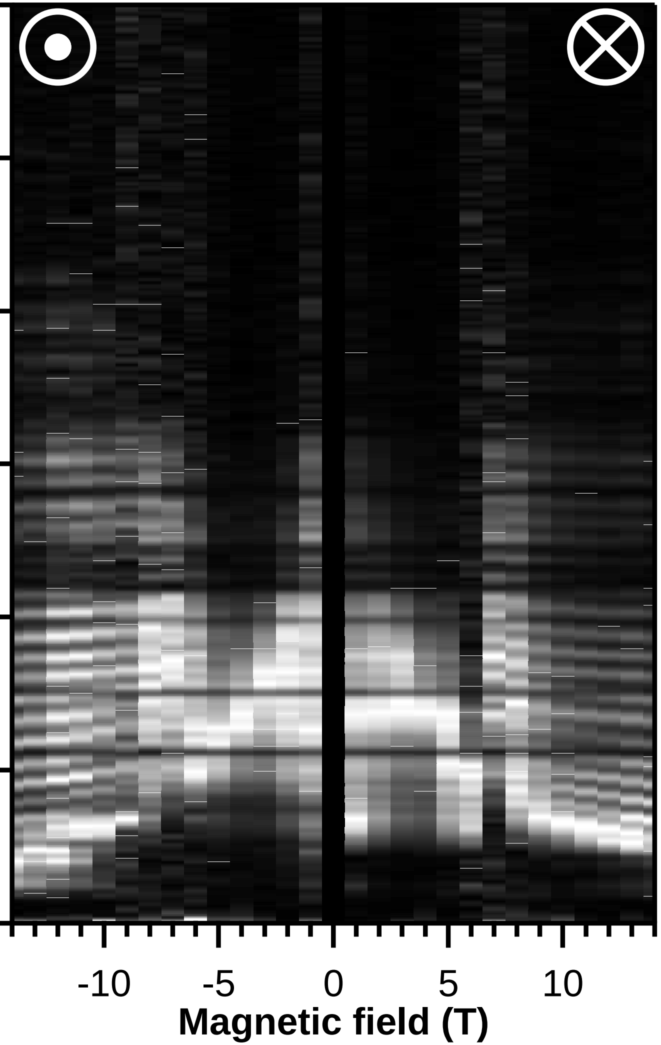
Max THz: 3 T

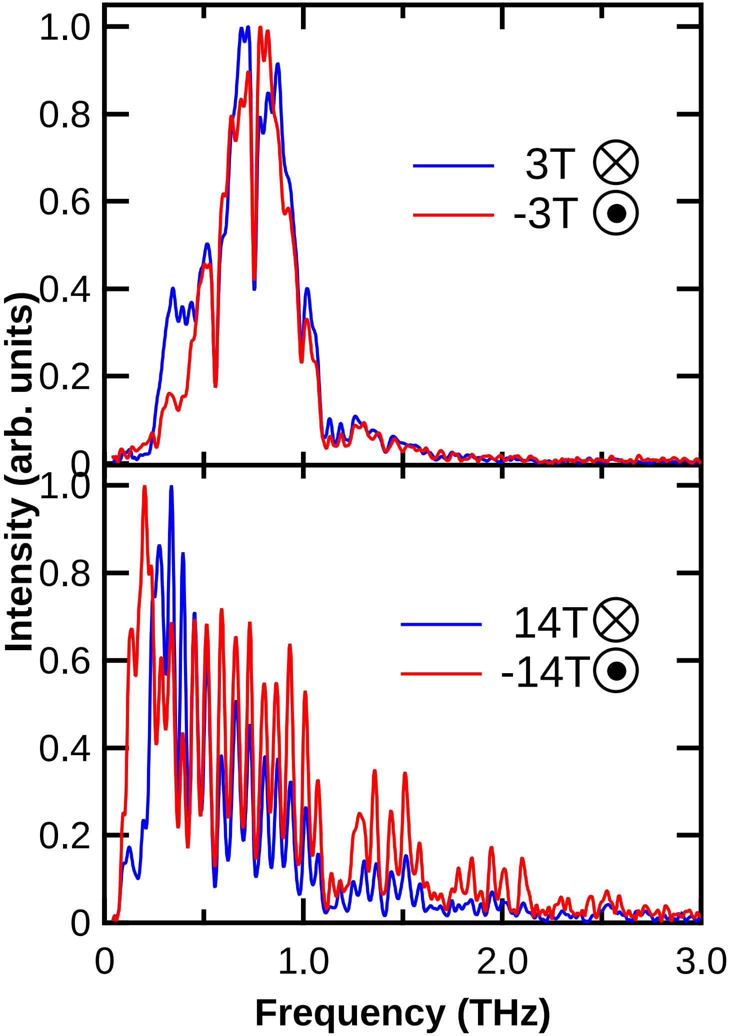
Min THz: 6.3 T

Constant ?: Over 10 T

Anomalous magnetic-field-direction dependent saturation is observed.

The radiation spectrum up to 14-T





Clear period
structure is
observed ov
10-T.

Parameters to design the practical THz-radiation source

@ Semiconductor → InAs[1]

Excitation source

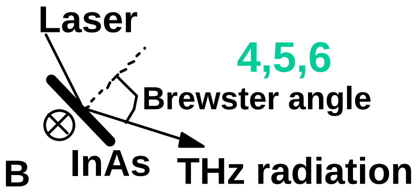
@ Pulse duration → 100 fs[2]

@ Power → Higher is better[1]

@ Surface Treatment → As polished[3]

@ Temperature → Room temperature[3]

@ Geometry →

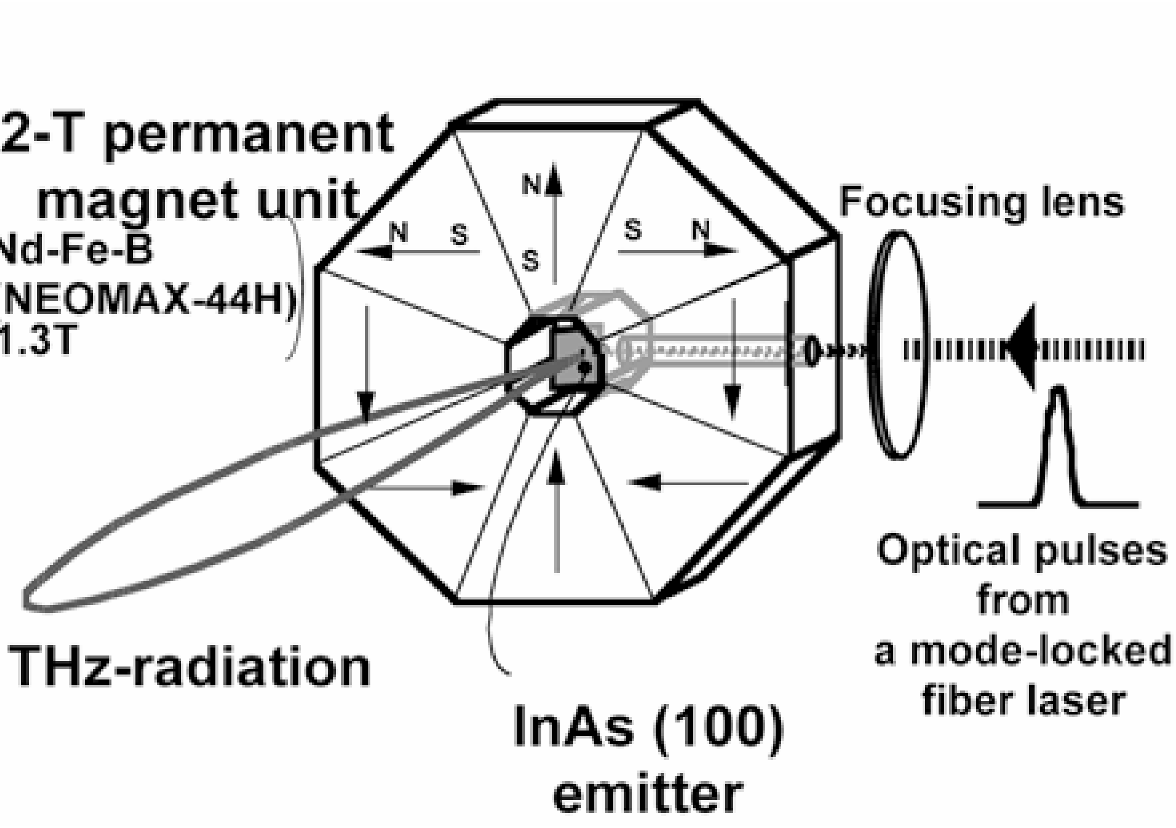


@ Magnetic Field → ~3T

1. JAP 84, 654 (1998
2. APL 75, 451 (1999
3. JJAP 38, 1186 (19
4. APL 76, 1398 (200
5. RSI 71, 554 (2000
6. AO 40, 1369 (2001

A few mW THz-radiation power will be obtained.

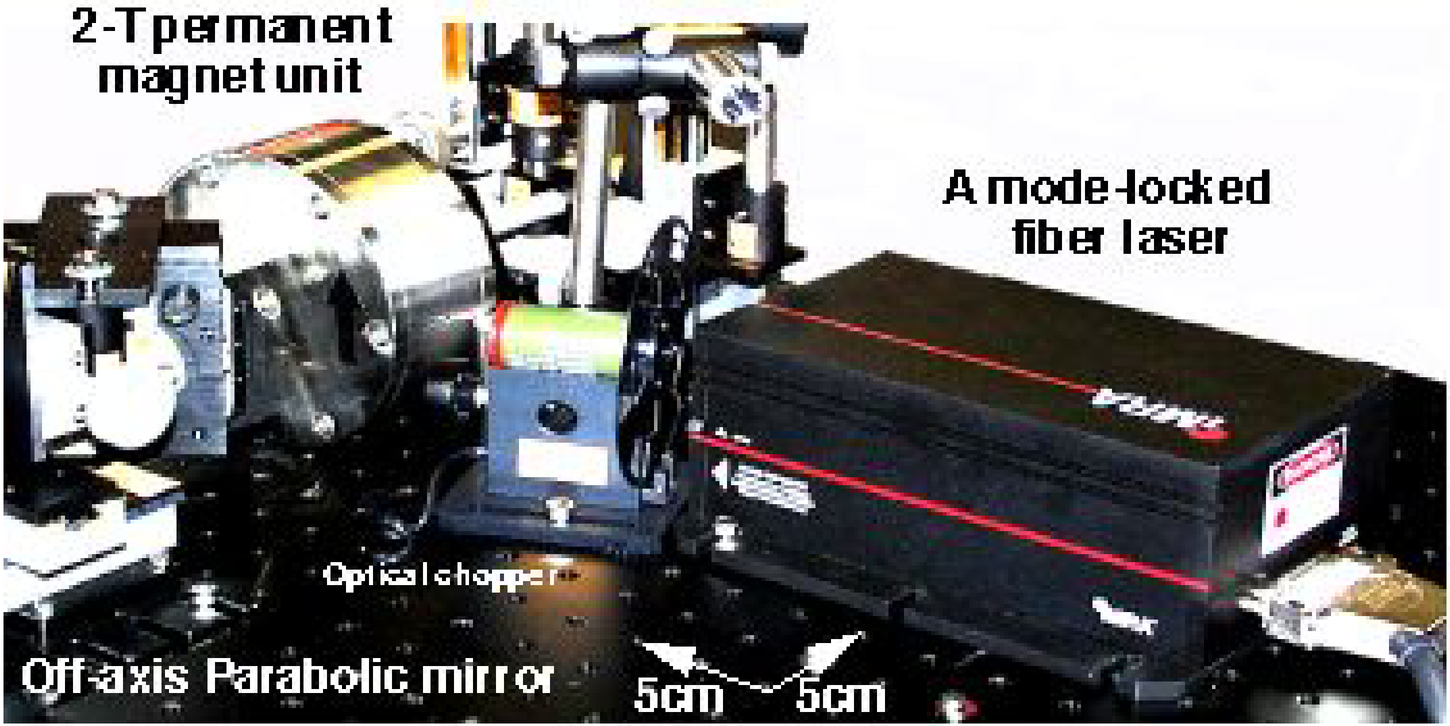
2-T Magnetic circuit consisting of 1.3-T permanent magnets



- @ 8 Nd-Fe-B pieces
  (1.3-T magnetic fie
- @ 5-kg weight
- @ 56-mm thickness
- @ 128-mm diameter
- @ 10-mm diameter
  center hole

The magnetic field in the center hole is 2T.

Compact THz-radiation source



RSI 71, 554 (2000)