

# 太赫兹物理、器件与应用

曹俊诚

信息功能材料国家重点实验室

中科院上海微系统所

2009.10.29@北大

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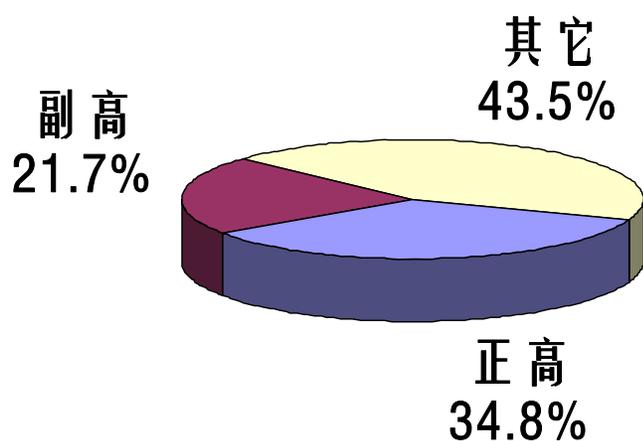
主要学科领域： 电子科学与技术； 信息与通信工程

THz研究依托： 信息功能材料国家重点实验室

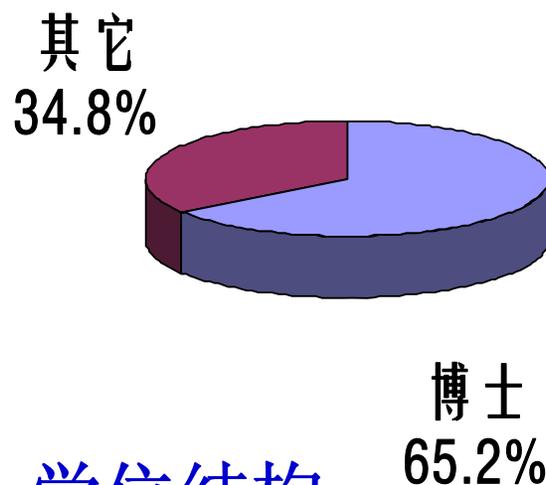


# 人员结构

固定人员46名，研究员16名（其中院士1名，二级8名），副高10名，30人有博士学位



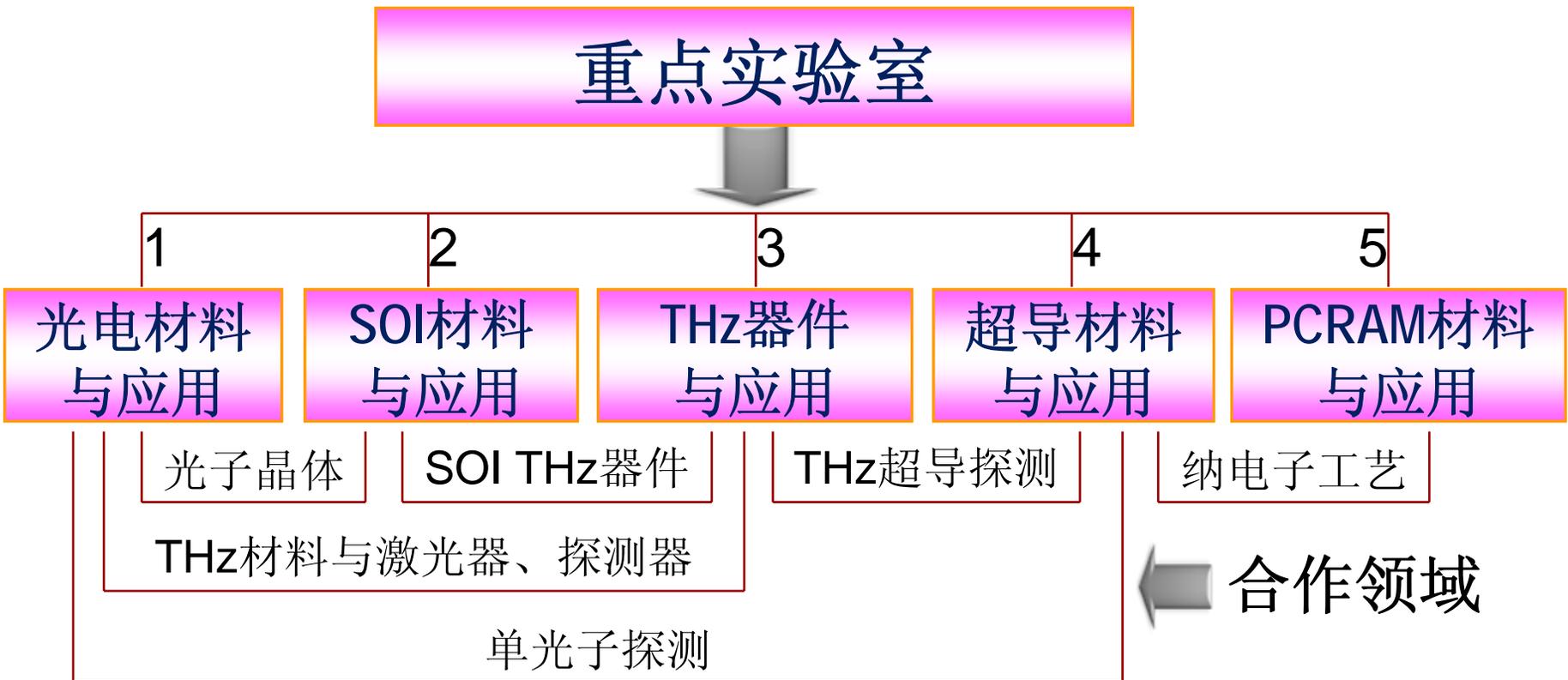
职称结构



学位结构

另外，有博士后8名，博士研究生47，硕士研究生42

# 科研方向

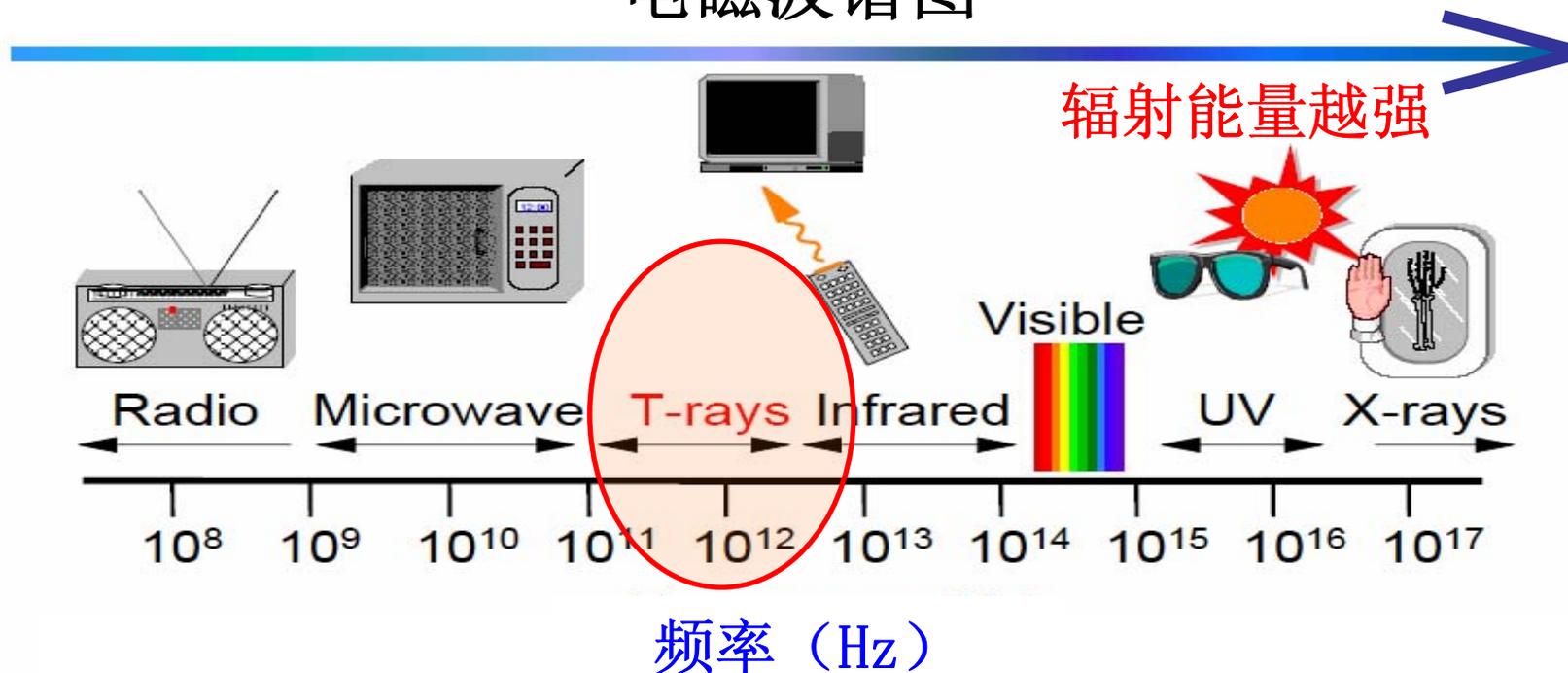


应用于：航天，通信、环保、健康等

# 背景与推动

# 太赫兹 (THz) 波

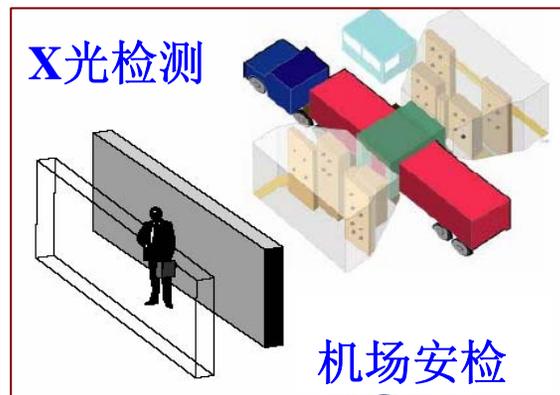
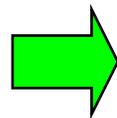
## 电磁波谱图



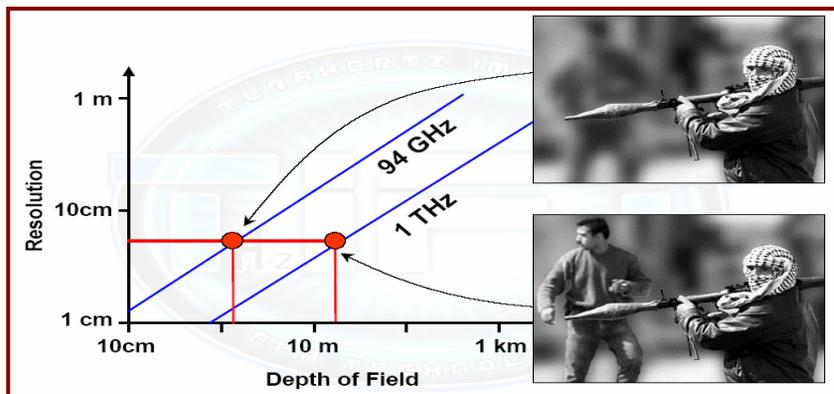
介于毫米波与红外光之间，频率在**0.1-10THz**（波长为**3毫米-30微米**）范围，又称**T-射线**

# THz波重要性

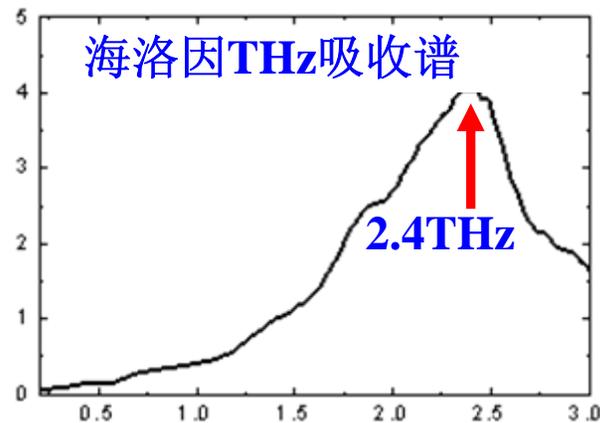
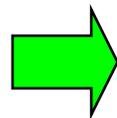
✓ 与X光相比，THz波能量低，不会破坏生物组织，具有很高安全性，适合安检和医学成像



✓ 与微波相比，THz成像分辨率更高；THz通信更保密、安全



✓ 与红外光比，THz特征光谱对很多大分子来说更易分辨，可很好地用于鉴别毒品和爆炸物等



# 研究状况

## 美国:

- 国防部、空军、能源部(THz连续、大功率源)
- 航天局(THz遥感)
- 国家卫生学会(THz医学成像)



## 欧盟:

- **StarTiger** THz空间计划、遥感、成像
- **THz-bridge** 生物医学诊断
- **Teravision** THz成像器件、THz相机



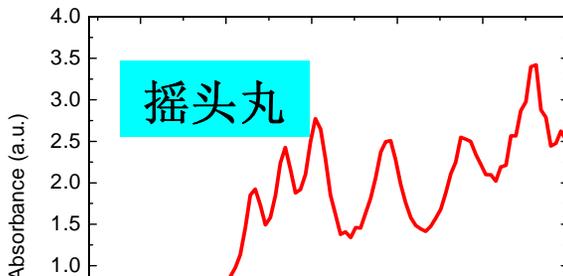
## 日本:

- 列为十年战略规划首位。发展THz病理诊断、毒品和爆炸物检测技术等

## 中国

# 国家重大需求

国家重点管制类毒品THz谱



全国

# THz辐射有望成为一种新的公共安全监控技术



Experts and engineers said...  
Houston - NASA investigators have concluded that a piece of foam that hit Columbia during its launch is what caused a hole to open in the front edge of the shuttle's left wing and allowed superheated air to burn it apart on re-entry.  
The conclusion is a turnaround for NASA. In the early days after Columbia disintegrated on Feb. 1, NASA top officials said they did not see how the foam insulation that fell off the external tank could have significantly damaged the shuttle's heat-protective skin. Administrator Sean O'Brien's detractors who had placed blame on the foam as "foam-shrapnel." NASA also ordered an engineering analysis conducted before Columbia's re-entry that said the foam hit would not pose a danger.  
Space agency engineers plan to brief the independent Columbia Accident Investigation Board, which is in charge of the probe, about their findings in a closed meeting Thursday.  
The foam impact quickly became a key suspect in the investigation, but other possible causes were not ruled out. Now, NASA investigators believe they have enough evidence to push aside other theories, officials and sources familiar with the investigation said.  
Officials said the board also suspects that the foam impact probably caused the disaster, but it does not agree entirely with NASA. The sources cautioned that



# THz振荡器和探测器

## 两个重大基础问题:

### ➤ THz振荡源:

自由电子激光器, 气体激光器

Gunn振荡器, Bloch振荡器

电光晶体

半导体THz振荡器

THz量子级联激光器 (THzQCL)

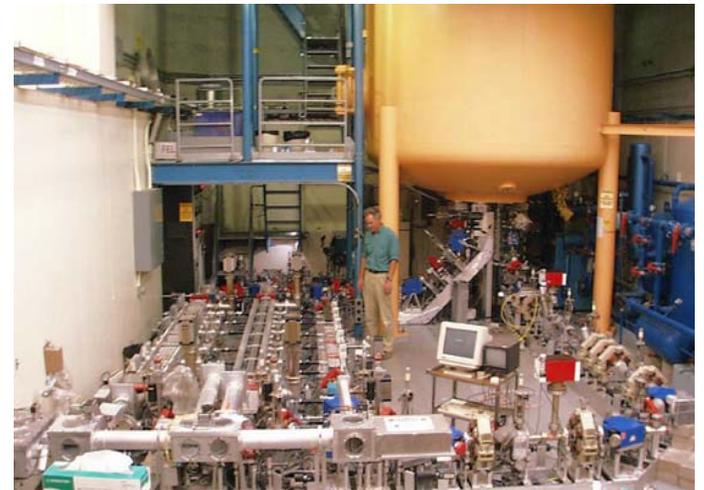
### ➤ THz探测器:

热辐射探测器

热电探测器

电光晶体

THzQWP



UCSB的自由电子激光器

# 各类THz源技术特点

## 自由电子激光器，同步辐射光源

- 输出频率覆盖范围宽
- 输出功率高
- 光束质量好
- 功耗高、体积庞大

## 返波管 (BWO)

- 输出频率范围 $<1.11\text{THz}$
- 输出功率1-10毫瓦
- 体积约 $0.5 \times 0.4 \times 0.5$ 立方米
- 功耗600瓦；重量45公斤

## Gunn振荡器

- 输出频率范围 $<1.0\text{THz}$
- 高频段输出功率低（微瓦）

## 维吉尼亚公司产品技术参数

- 100-300 GHz 输出功率1-30mW
- 300-600 GHz 输出功率 0.1-8mW
- 600-900 GHz 输出功率 10-500微瓦
- 1.0-1.7 THz 输出功率 1-60微瓦

## CO<sub>2</sub>泵浦小分子气体THz激光器

- 输出频率准连续（更换工作介质可覆盖0.3-7.0THz）
- 输出功率 $>50$ 毫瓦
- 光束质量高
- 重量约70公斤
- 结构复杂；功耗约3千瓦

## 飞秒激光泵浦、差频THz发生器

- 输出频率范围 $<3.0\text{THz}$
- 输出功率低 $<$ 毫瓦量级
- 功耗高、结构复杂、难于集成

## P-Ge振荡器；半导体负有效质量振荡器；基于带内反射的THz振荡器；超晶格Bloch振荡器

- 新器件概念、原型器件阶段，无成熟器件、发展有很大不确定性

# 各类THz探测器技术特点

## 半导体肖特基二极管

- 体积小、重量轻
- 响应频段<2.5THz
- 外差探测，需THz本地振荡源

## THz量子阱探测器

- 按需设计响应频段
- 响应速度快
- 灵敏度较高
- 体积小、稳定、寿命长
- 制冷需求高（20-50K）

## 超导体—绝缘体—超导体隧穿结探测器

- 体积小、重量轻
- 探测灵敏度高，逼近量子极限
- 响应频段<1.5 THz
- 制冷温度约4K
- 需THz本地振荡源

## Bolometer; Pyroelectric detector

- 探测率低
- 响应速度慢，通信速度提不上去
- 无光谱分辨本领

## 利用低维结构中THz引起的等离子体振荡

- 新器件概念，原理型器件阶段

**一、 THz探测器与物理**

**二、 THz激光器与物理**

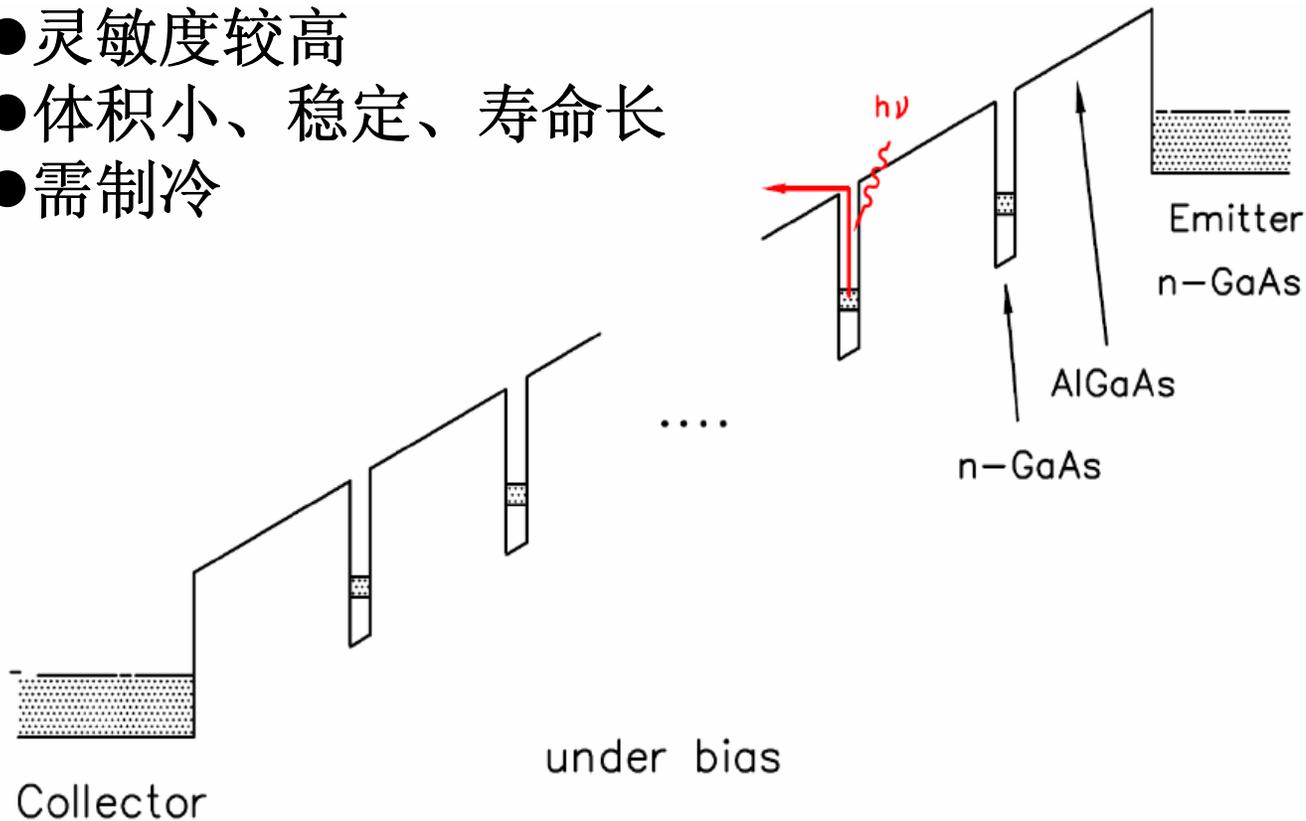
**三、 THz通信初步**

# THz量子阱探测器 (THzQWP)

# THz量子阱探测器特点

## THz量子阱探测器（THzQWP）

- 按需设计响应频段
- 响应速度快
- 灵敏度较高
- 体积小、稳定、寿命长
- 需制冷



# THzQWP主要工作

- ◆ 基于THz感生的碰撞离化模型，解释了THz场在低维半导体的吸收规律；合作研制了2-7 THz QWP
  - **Phys. Rev. Lett. 91, 237401 (2003)**
  - **Phys. Rev. B 69, 165203 (2004).**
  - **Appl. Phys. Lett. 84, 4068 (2004)**
- ◆ 计算了GaAs光学声子吸收对THzQWP的光谱响应的影响；研制了提高THzQWP吸收系数的新结构(改变阱宽和掺杂)，吸收系数超过20%，以实现高速探测
  - **Infrared Physics and Technology 47, 169 (2005)**
  - **IEEE J Sel Top Quant Elect 14, 374 (2008)**
- ◆ 研究了多体效应对THzQWP响应峰位影响
  - **Appl. Phys. Lett. 94, 201101 (2009)**

# 发展了THz感生的碰撞离子化模型

VOLUME 91, NUMBER 23

PHYSICAL REVIEW LETTERS

week ending  
5 DECEMBER 2003

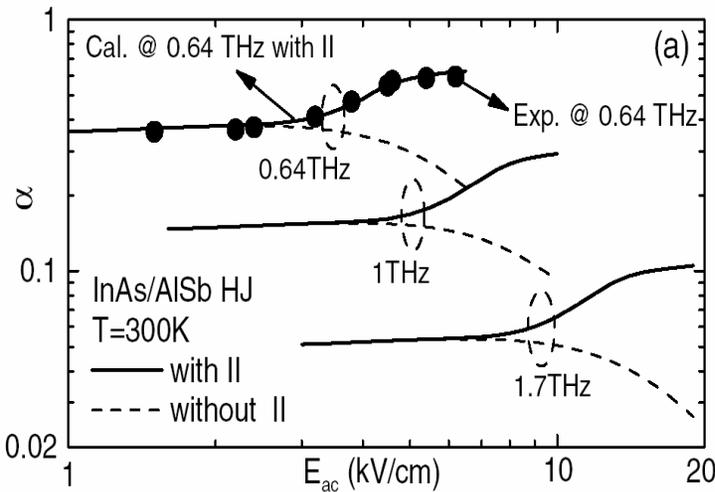
## Interband Impact Ionization and Nonlinear Absorption of Terahertz Radiation in Semiconductor Heterostructures

J. C. Cao

*for Informatics, Shanghai Institute of Microsystem and Information Technology,  
5 Changning Road, Shanghai 200050, People's Republic of China  
February 2003; published 1 December 2003)*

ed nonlinear free-carrier absorption of terahertz (THz) radiation in  
sidering multiple photon process and conduction-valence interband  
etermined the field and frequency dependent absorption rate. It is  
atterings are important at low to intermediate field, and (ii) most  
otion is dominated by II processes. Our theory can satisfactorily  
ital result on the nonlinear absorption in the THz regime.

PACS numbers: 78.20.Ci, 72.10.Bg, 73.50.Fq, 73.50.Gr



利用THz感生的电子-空穴对的产生机制解释了THz吸收过程。表明：

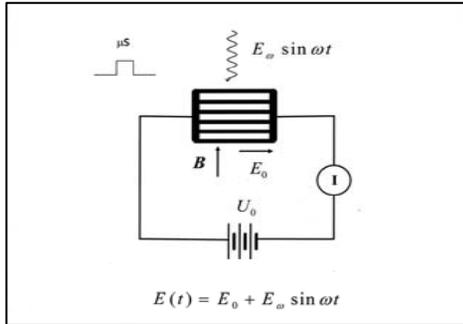
- (1) 电子无序散射是低场强和中等场强下的主要决定因素。
- (2) 高场强下的吸收则主要由带间碰撞离子化决定。

J. C. Cao, Phys. Rev. Lett. 91, 237401 (2003).

J. C. Cao, Phys. Rev. B 69, 165203 (2004).

应用于THz探测器设计

# THz引起的e-h对的产生



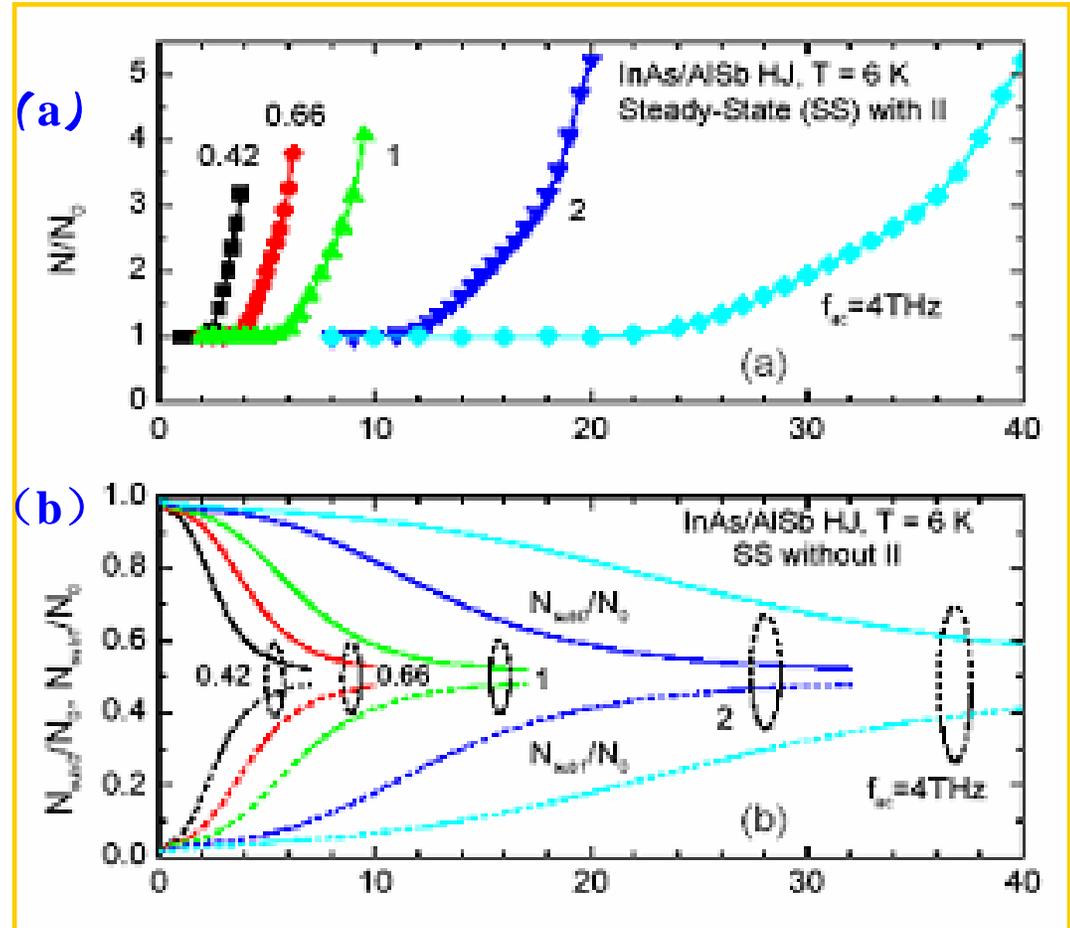
THz电磁波辐射在异质结上

THz辐射:

$$E(t) = E_0 + E_{ac} \sin(2\pi f_{ac} t)$$

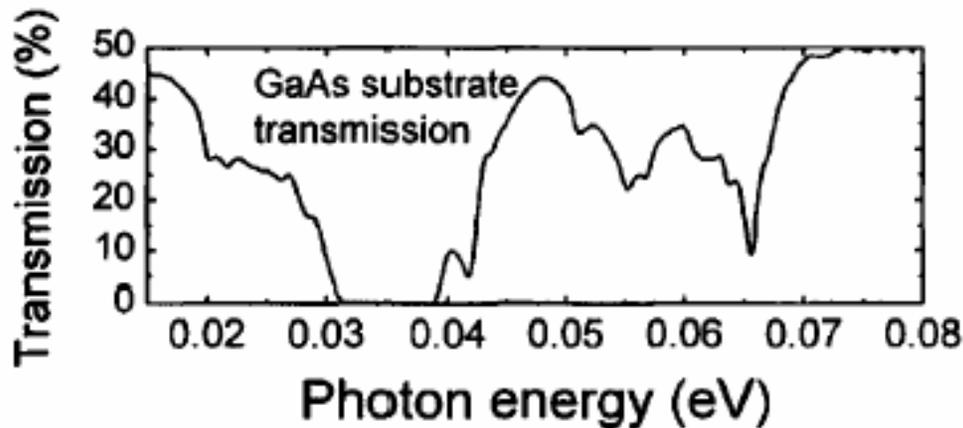
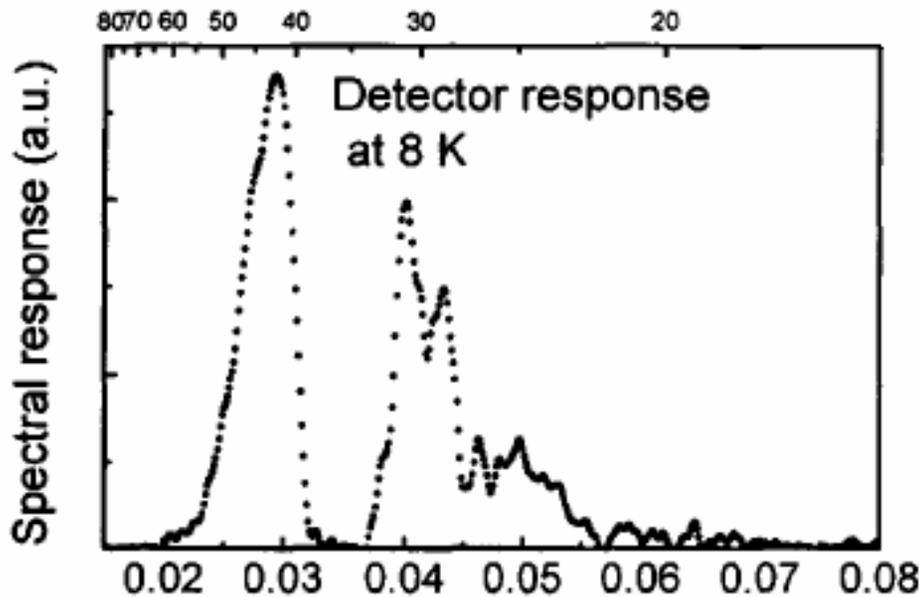
电光耦合系数:  
 $r = eE_{ac} / (mw^2)$

J. C. Cao & X. L. Lei, *Phys. Rev. B* **67**, 085309 (2003).



(a) 电子-空穴对的产生  $\sim$  THz辐射强度  
 (b) 不同子带电子占据率  $\sim$  THz辐射强度

Wavelength ( $\mu\text{m}$ )



## THzQWP研制

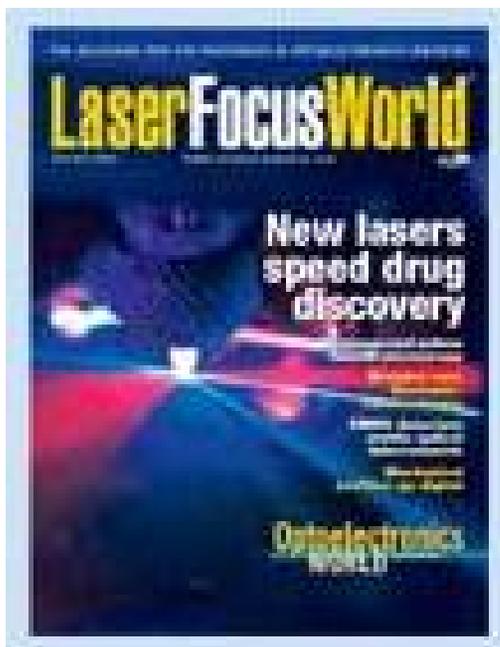
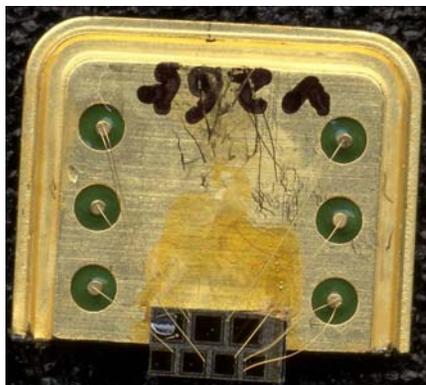
实现了一种能工作在光子能量小于 34 meV 的 THzQWP，其峰值探测频率为 2-7 THz。探测灵敏度达  $10^{-12}$  量级

Appl. Phys. Lett. 84, 4068 (2004).

Infrared Physics and Technology 47, 169 (2005).

IEEE J Sel Top Quant Elect 14, 374 (2008) (Invited paper)

# 2004年在国际上率先研制了2-7 THz QWP。美国 Laser Focus World 报道了我们的工作



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### Newsbreaks

#### InGaN-based surface-emitting laser has a horizontal cavity

Although it's not a VCSEL (vertical-cavity surface-emitting laser), researchers at NTT (Atsugi, Japan) and the University of Electro-Communications (Chofu, Japan) have created a surface-emitting indium gallium nitride (InGaN)-based blue-violet laser diode. Surface-emitting lasers, common in the red and infrared wavelengths in the form of VCSELs, are far easier to fabricate than edge emitters because they don't have to be cleaved. Ongoing efforts to create an InGaN-based VCSEL have not yet borne fruit. The Japanese researchers sidestepped the problem by fabricating a horizontal-cavity InGaN laser along with an angled mirror just beyond the end of the cavity.

The angled output mirror and the vertical cavity mirror are created by dry etching and selective regrowth of a magnesium-doped GaN layer; the mirrors are very smooth with little angular misalignment. The room-temperature, electrically pumped laser emits 0.3- $\mu$ s pulses at 405 nm and a 1-kHz repetition rate. The output mirror lies at a crystal plane 58° from the vertical, so the beam is not vertical, but is emitted at an angle of 28° from the surface normal. The method enables wafer-scale fabrication of blue-emitting semiconductor lasers. Contact Tetsuya Akasaka at akasaka@will.brl.ntt.co.jp.

RESOURCE GUIDE

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#### Terahertz QWIP responds at 42 $\mu$ m

A terahertz quantum-well infrared photodetector (QWIP) with a response that extends below the optical phonon energy of gallium arsenide (GaAs) has been developed by researchers at the National Research Council (Ottawa, Ont., Canada) and the Chinese Academy of Sciences (Shanghai, China). Previously, absorption by GaAs optical phonons contributed to making the 36- $\mu$ m and longer (9-THz and below) region of the spectrum inaccessible to QWIPs.

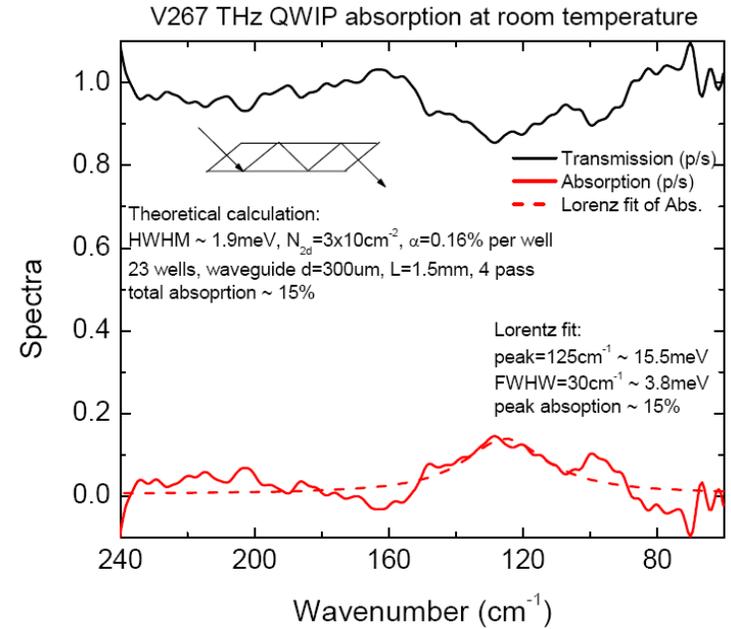
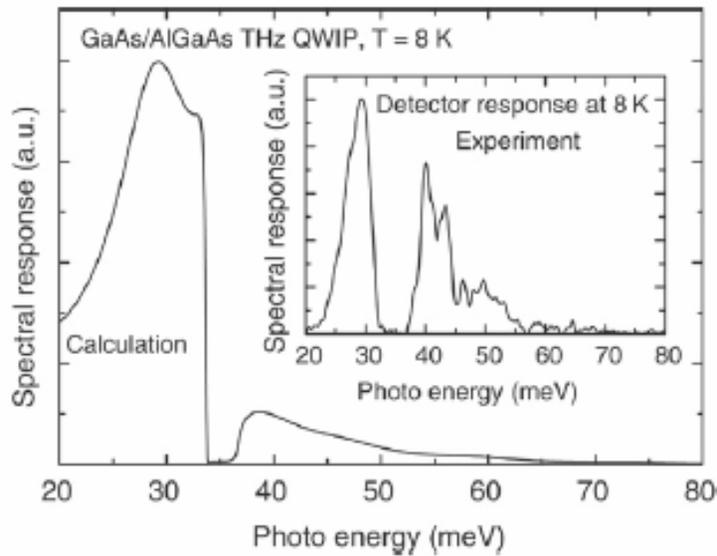
The aluminum (Al) content of the 40-nm AlGaAs barriers was kept to no greater than 5%; 50 12-nm-thick GaAs quantum wells completed the structure. Although the device still did not respond to a wavelength band between 34 and 39  $\mu$ m, it did exhibit response at longer wavelengths, peaking at 42  $\mu$ m. But, although theoretically the device should have reached background-limited infrared performance (BLIP) as its temperature was lowered to about 15 K, it did not; instead, at about 15 K the dark current stopped decreasing—an effect most likely the result of tunneling. The researchers will test wider and less-impure barriers to suppress the tunneling current. Terahertz QWIPs for even-longer wavelengths are in the works. Contact Hui Chun Liu at h.c.liu@nrc.ca.

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# THz量子阱探测器优化



计算了GaAs光学声子吸收对THzQWP的光谱响应的影 响。研究表明，GaAs光学声子对34—36meV区域有很强的吸收。理论计算与实验很好符合。

THzQWP的透射与吸收谱

Superlattices and Microstructures 40, 119 (2006).

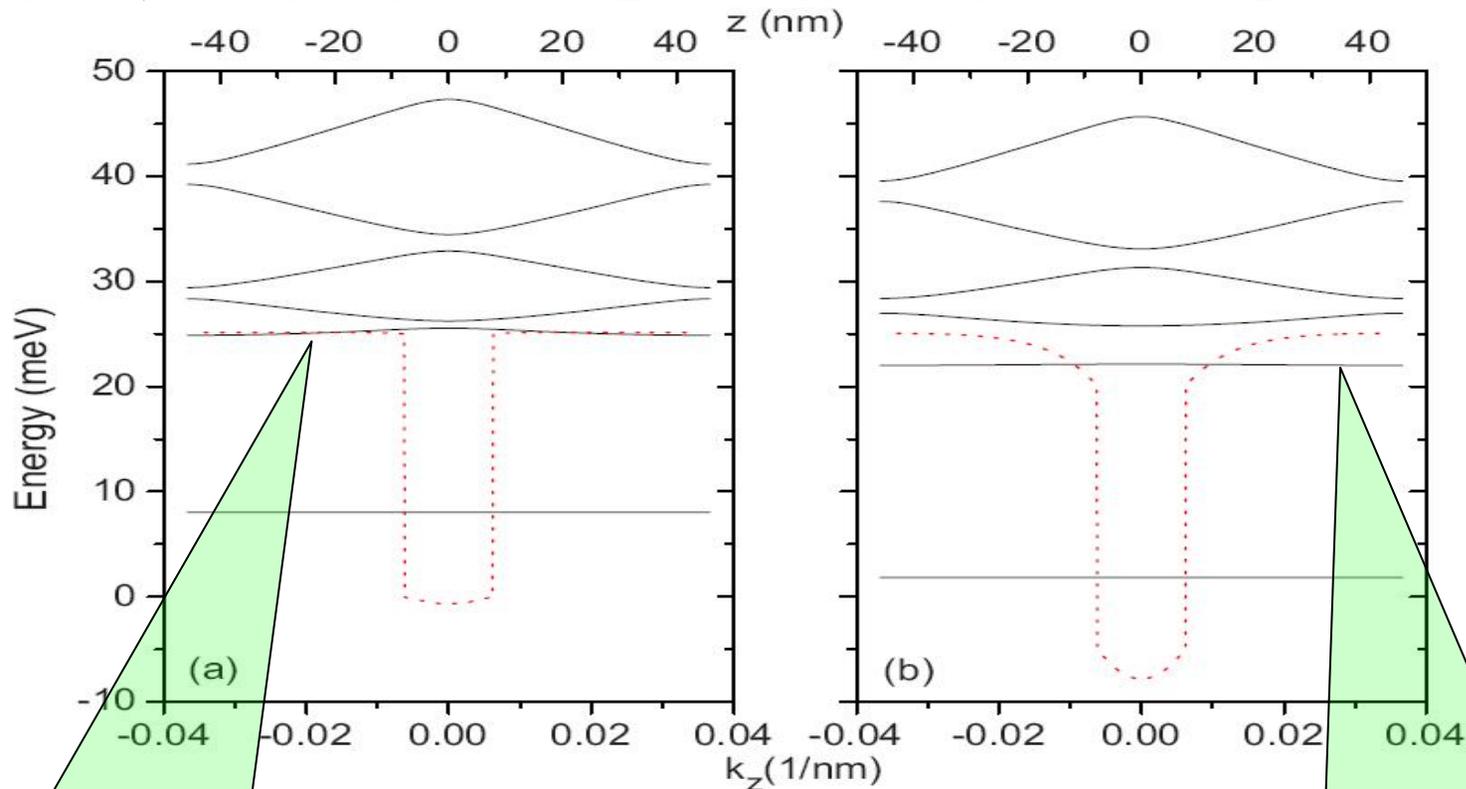
Infrared Physics & Technology 50, 191 (2007).

# 多体效应对THzQWP响应峰位影响

Appl. Phys. Lett. 94, 201101 (2009)

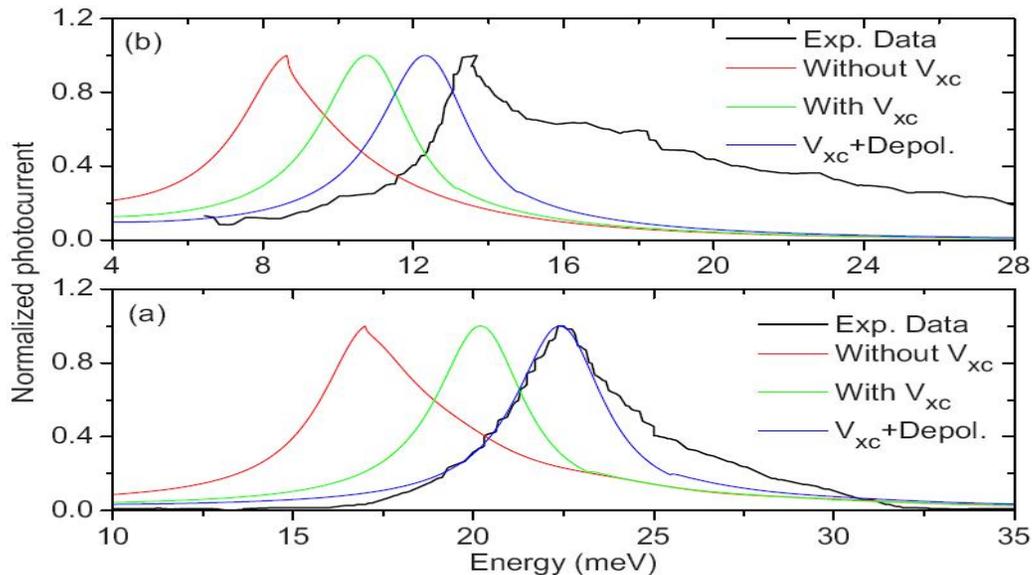
在Hartree近似下，响应峰位设计误差约为**30%**！

多体效应：交换关联（静态）；去极化、类激子（动态）



在不考虑交换关联作用时，设计的器件结构能够保证第一激发态与垒高一致，**最佳设计**！

考虑交换关联作用，第一激发态处于量子阱中，**非最优设计**！



设计误差大幅减小  
30% → 约5%

Appl. Phys. Lett. 94, 201101 (2009)

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Many-body effects on terahertz quantum well detectors

X. G. Guo, Z. Y. Tan, J. C. Cao, and H. C. Liu

Appl. Phys. Lett. 94, 201101 (2009) (3 pages)

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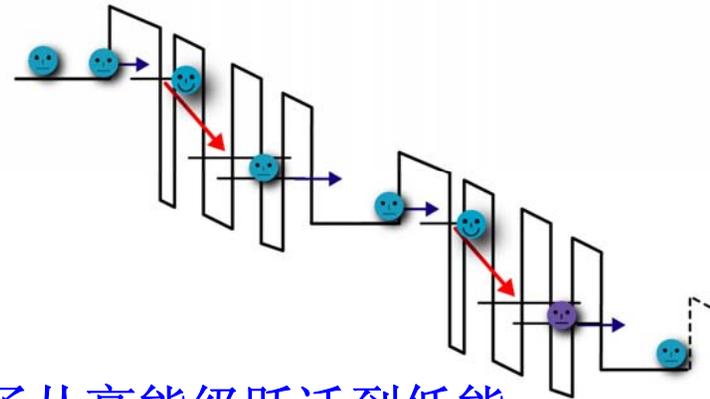
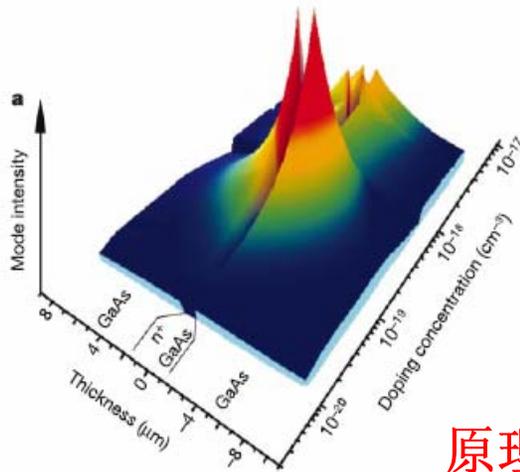
一、 **THz**探测器与物理

二、 **THz**激光器与物理

三、 **THz**通信初步

# THz量子级联激光器

量子级联新结构的应用使得激光波长从红外波段提升了10倍，推进到THz波段(2002)



原理：电子从高能级跃迁到低能级释放出THz辐射

Kohler et al, NATURE 417, 156 (2002)

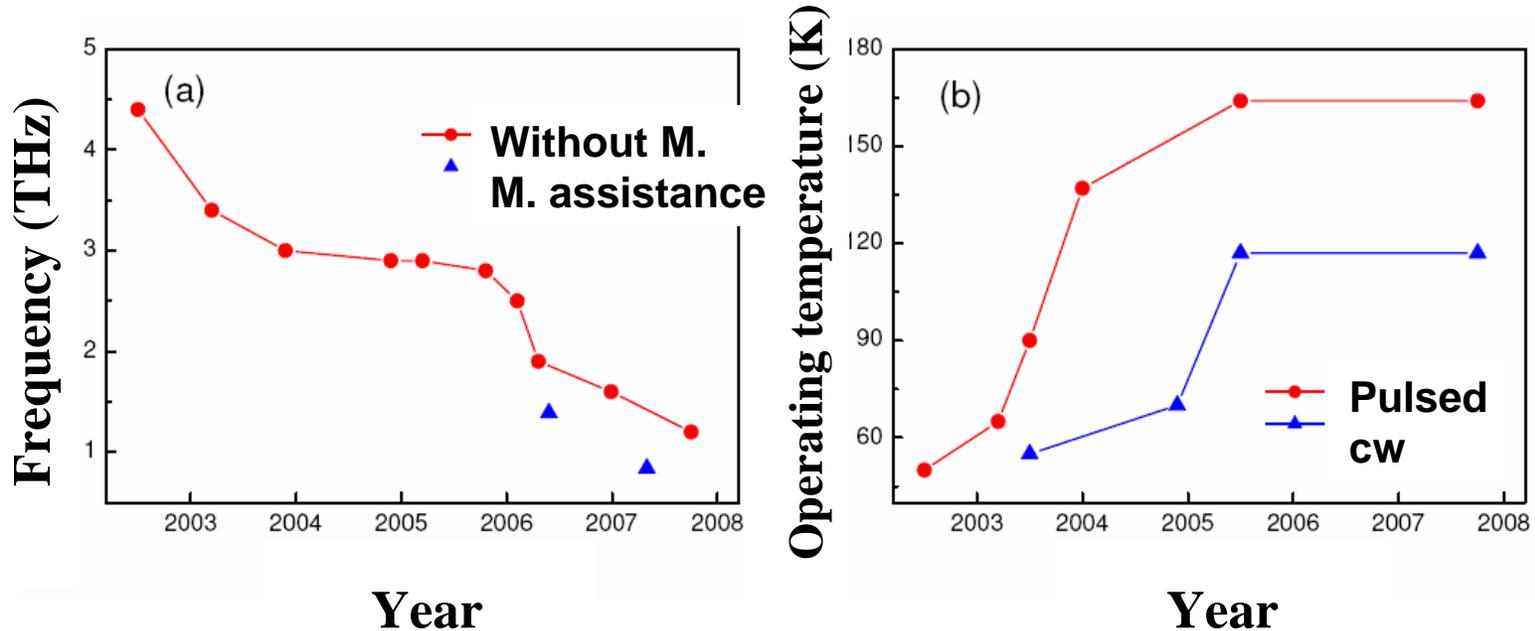
# THzQCL主要工作

- ◆ 发展了THzQCL MC模拟程序，设计了基于共振声子散射的THzQCL。研究了子带激光器动力学
  - **Phys. Rev. Lett. 90, 077402 (2003)**
  - **Appl. Phys. Lett. 88, 061119 (2006)**
  - **J. Appl. Phys. 104, 043101 (2008)**
- ◆ 完成了THzQCL材料生长、器件制作
  - **Appl. Phys. Lett. 90, 041112 (2007)**
  - **Appl. Phys. Lett. 92 221105 (2008)**
  - **J. Appl. Phys. 103, 103113 (2008)**
- ◆ 优化了THzQCL器件设计
  - **Semicond. Sci. Technol. 23, 125040 (2008)**
  - **Semicond. Sci. Technol. 24, 065012 (2009)**
  - **J. Phys. D: Appl. Phys. 42, 025101 (2009)**

# Roadmap of THzQCL

- ✓ **The first THzQCL - Köhler *et.al*, Nature 2002 (Pisa, Italy)**
  - ***Chirped-superlattice***
  - ***Semi-insulating surface plasmon waveguide***
  - ***Lasing at 4.4 THz***
  - ***Maximum operating temperature of 50 K***
- ✓ **J. Faist, APL 2002**
- ✓ **Q. Hu, APL 2003**
- ✓ **H. C. Liu, NRC, APL 87, 141102 (2005)**
- ✓ **J. C. Cao's Group, SIMIT, Shanghai, 2007**

# Progress of THzQCL



Up to date, the best device performances are:

- maximum operating temperature  
**186 K (pulsed); 117 K (cw)**
- highest output power  
**250 mW**
- lowest lasing frequency  
**1.2 THz**

# THzQCL MC模拟

# Monte Carlo Method

- Used to solve mathematical problems by random-number technology
- Using random numbers in an essential way to simulate scattering processes
- The differential-integral equations usually include high-order numerical integrations

# MC solution of Boltzmann equation

The semi-classical BE for transport of Bloch electrons:

$$\frac{\partial f(r, k, t)}{\partial t} = -\frac{1}{\hbar} \nabla_k E(k) \cdot \nabla_r f - \frac{F}{\hbar} \cdot \nabla_k f + \left. \frac{\partial f}{\partial t} \right|_{coll},$$

Where  $\left. \frac{\partial f}{\partial t} \right|_{coll}$  can be replaced by collision integral:

$$\left. \frac{\partial f}{\partial t} \right|_{coll} = \frac{V}{8\pi^3} \int dk \{ f(r, k', t)(1 - f(r, k, t))\Gamma_{k'k} - f(r, k, t)(1 - f(r, k', t))\Gamma_{kk'} \}.$$

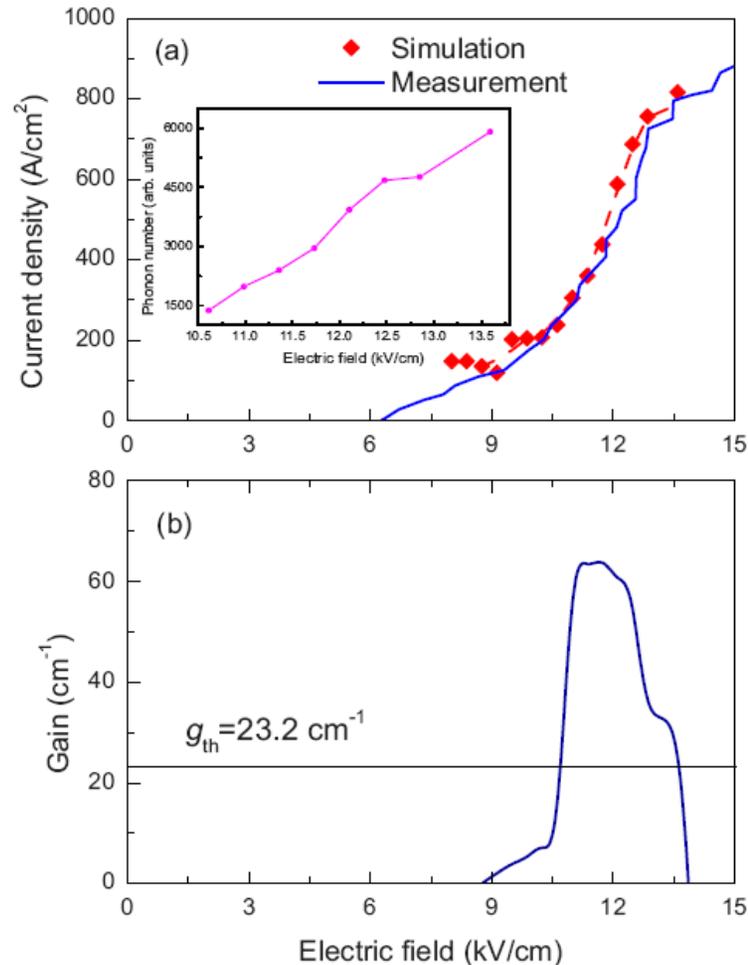
# I-V和器件调谐特性模拟与实验

Appl. Phys. Lett., 89, 211115 (2006)

J. Appl. Phys. 103, 103113 (2008)

J. Appl. Phys. 104, 043101 (2008)

Appl. Phys. Lett. 92, 221105 (2008)



对于四阱共振声子THzQCL，考虑电子-电子、电子-杂质、电子-LO声子散射以及热声子效应之后，模拟的*I-V*曲线和实验测量结果十分吻合。

设计偏压 **11kV/cm**（对应 **12V**），峰值增益 **66cm<sup>-1</sup>**，辐射频率**4.1THz**

计算的激射范围：**10.2-13 V**

测量的激射范围：**10.9-13.3 V**

# THzQCL参数优化

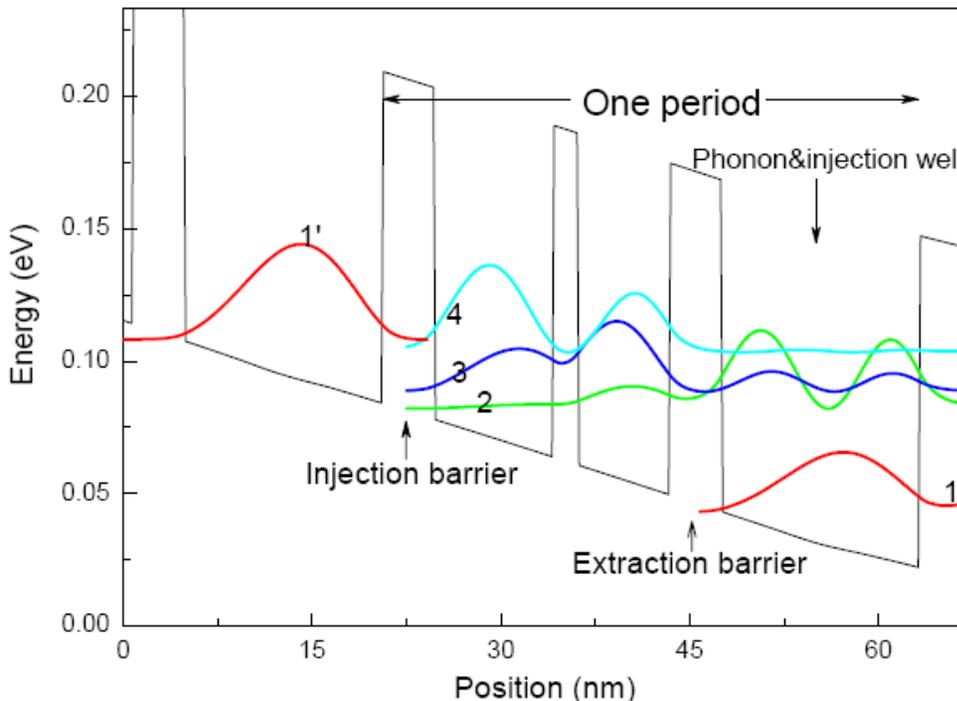
Appl. Phys. Lett. 92, 221105 (2008).

Semicond. Sci. Technol. 23, 125040 (2008)

Semicond. Sci. Technol. 24, 065012 (2009)

DUT: Three-well resonant-phonon THz QCL

We have simulated the effects of three parameters, i.e., **doping concentration, injection and extraction barrier width, and phonon extraction level separation** on the device performance.

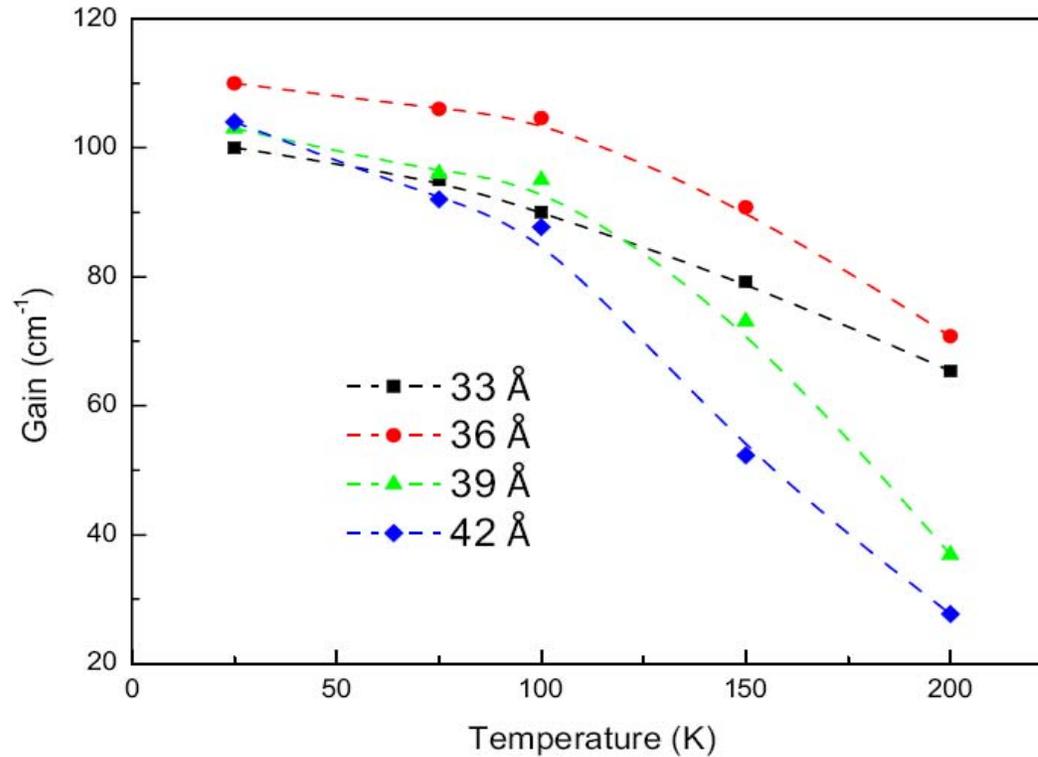


Designed bias: 14.4 kV/cm  
Lasing transition occur from level 4 to 3, and levels 3 (2) to 1 are for LO-phonon depopulation

Optimizing process:  
Injection barrier width  
→ extraction barrier width  
→ doping concentration

# Gain dependence on extraction barrier width

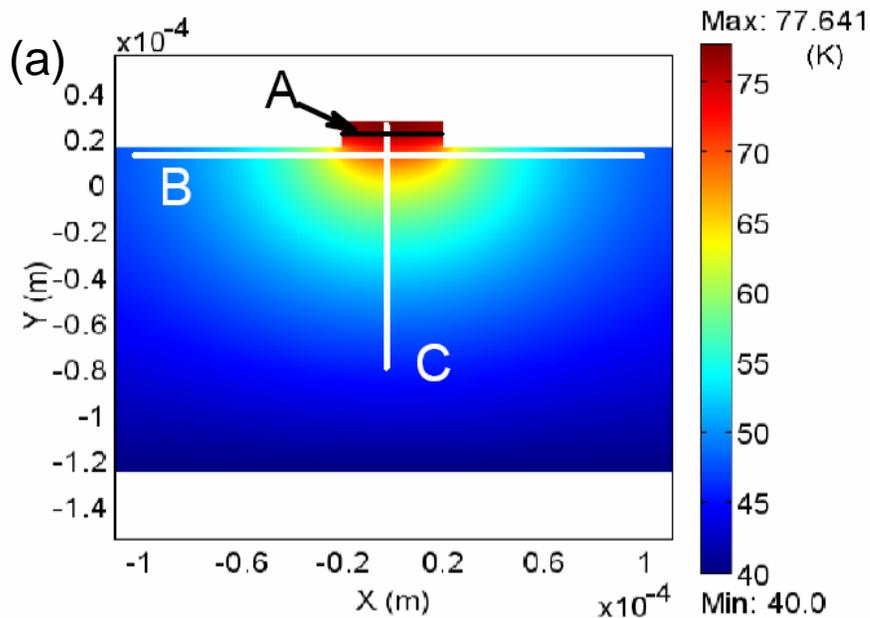
Appl. Phys. Lett. 92, 221105 (2008)



**The optimized extraction barrier width for maximal gain is 36 Å, which are in good agreement with the measured results.**

# THzQCL内部温度分布模拟

J. Phys. D: Appl. Phys. 42, 205102 (2009)



采用有限元方法模拟计算了THz QCL器件内部温度分布如图

(a) 所示。器件有源区的温度要远远高于热沉温度。

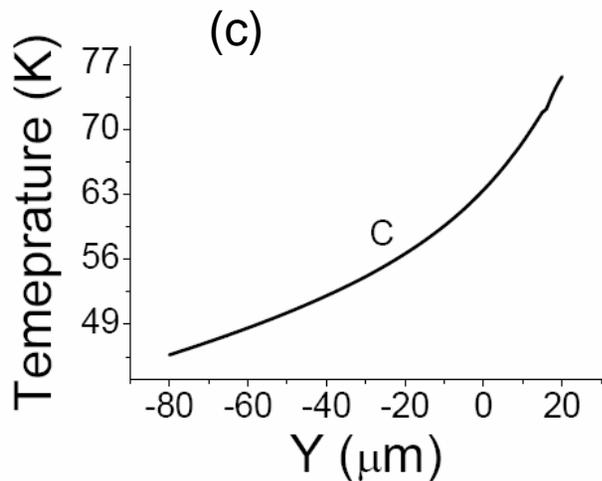
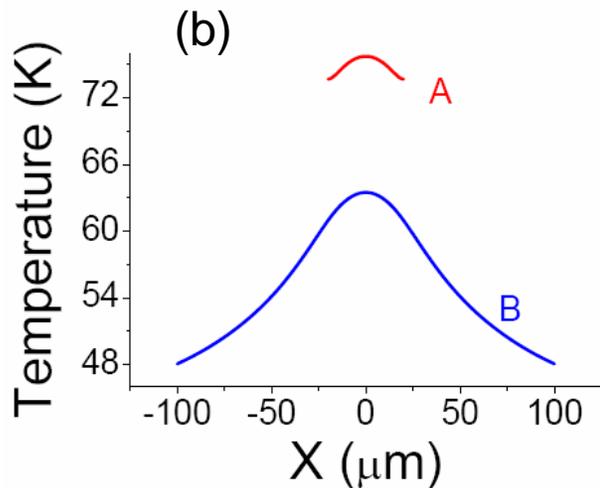


图 (a) 中的A、B、C三条直线所对应的温度梯度分别如图 (b)

(c) 所示。

# THzQCL研制与测试

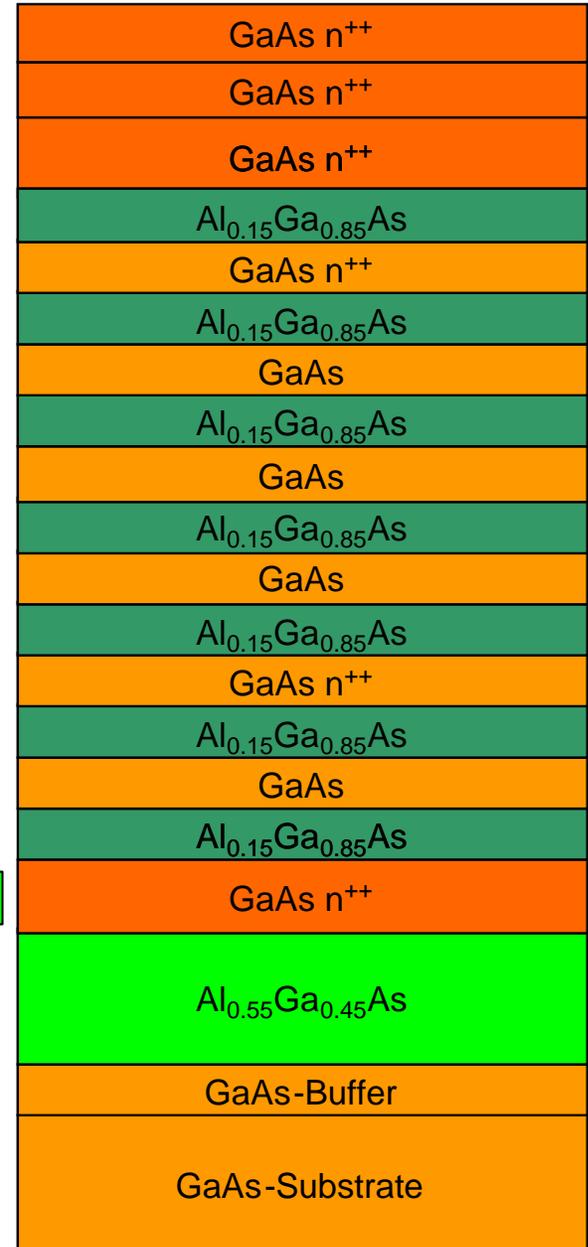
# THzQCL研制流程



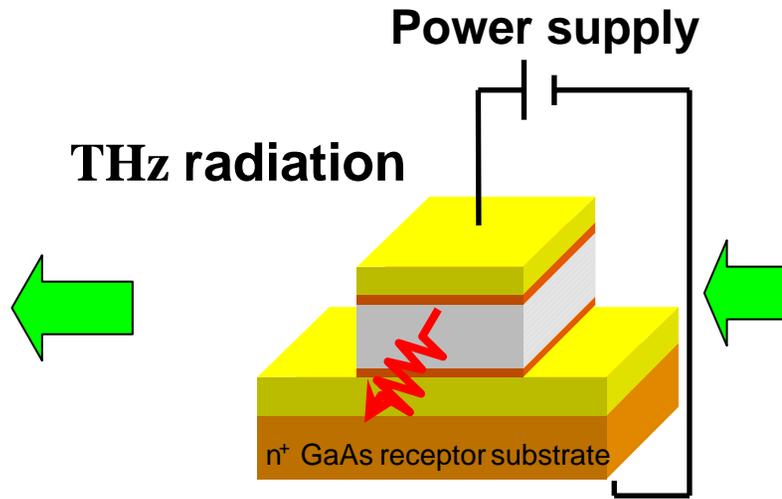
Cluster Simulation



V90 GSMBE  
Material growth

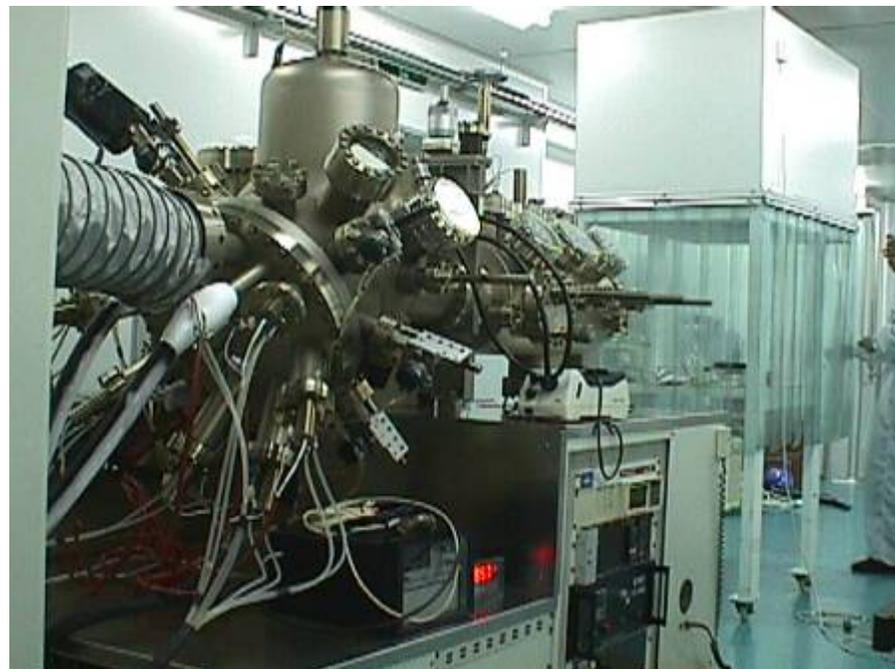


Packaged device



Fabrication

# THz量子器件材料生长设备



气态源分子束外延 (GSMBE) 系统

**V90** GSMBE

**V80** GSMBE

# THz器件、材料表征设备



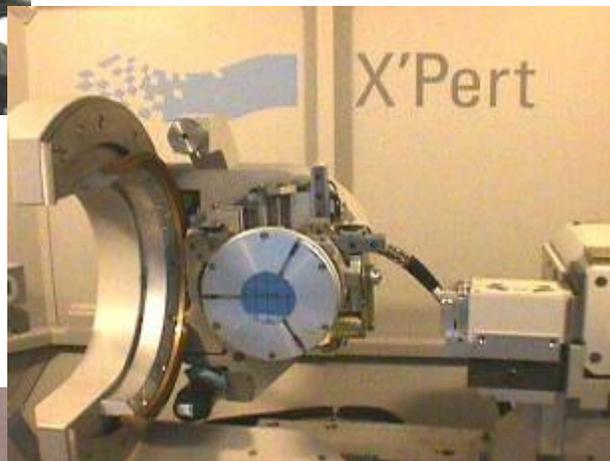
FTIR Spectroscopy

ECV, PVS & Hall



UV-Vis Spectroscopy

I-V, I-P & C-V

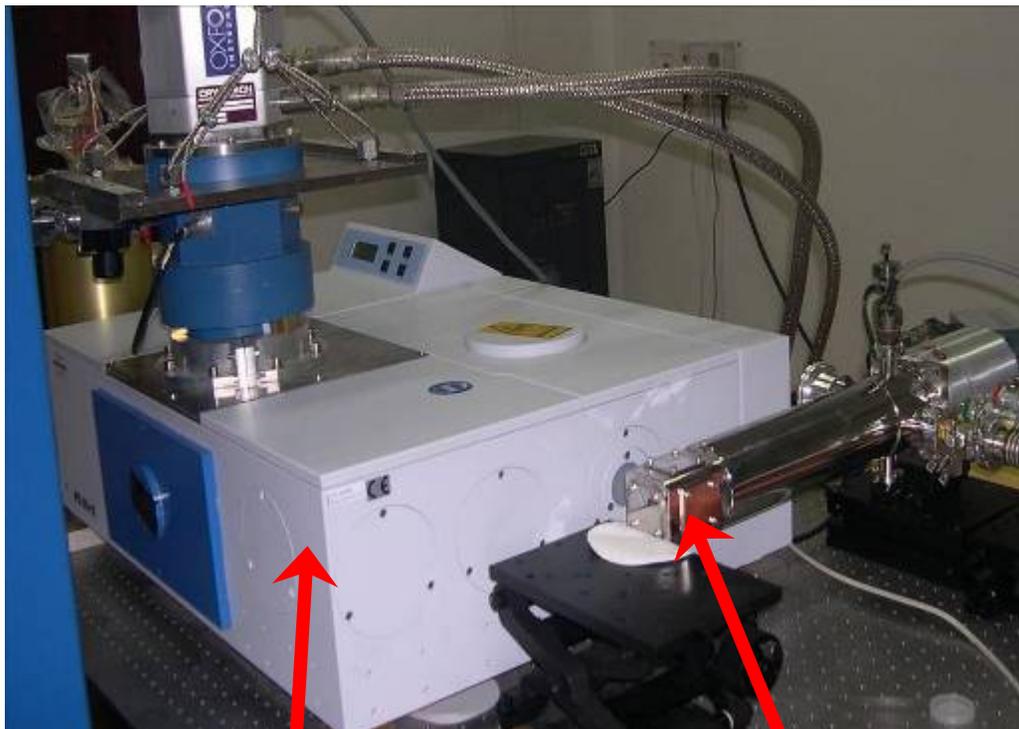


X-ray Diffraction



# THz器件测试

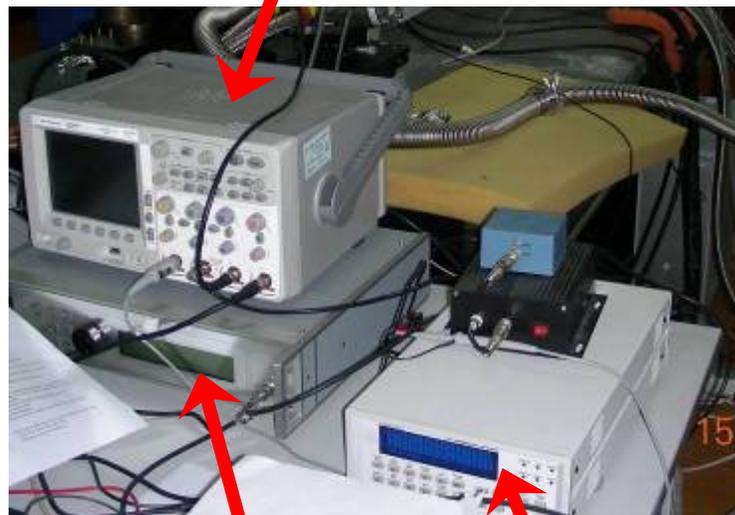
光谱测量装置



傅立叶红外光谱仪  
DTGS探测器

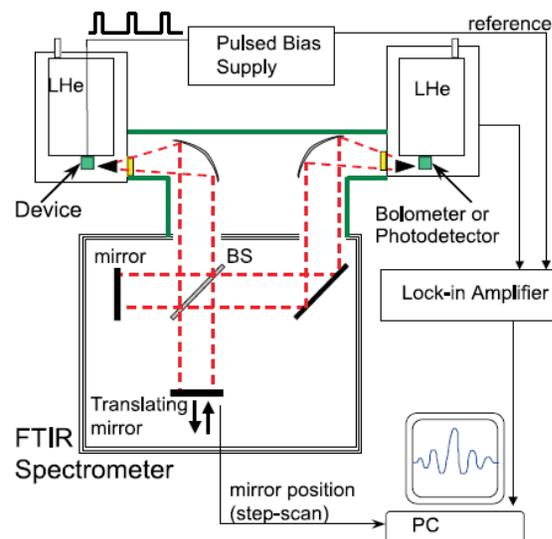
THzQCL器件

示波器



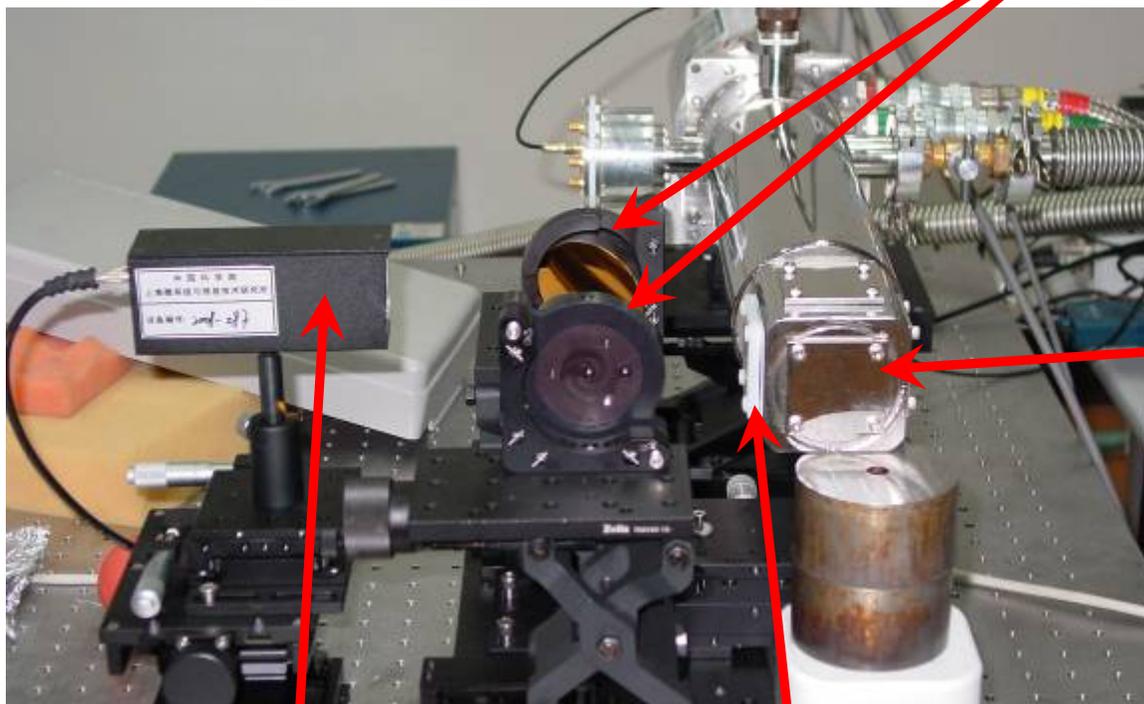
脉冲电源

温控仪



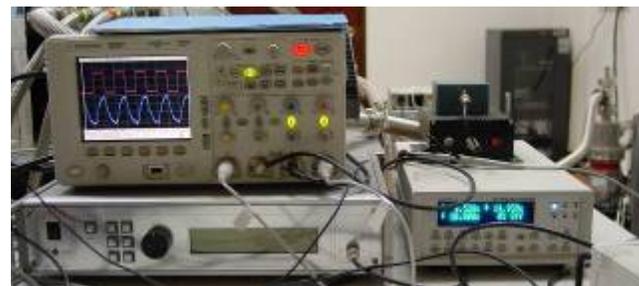
# THz器件光功率测量

离轴抛物镜

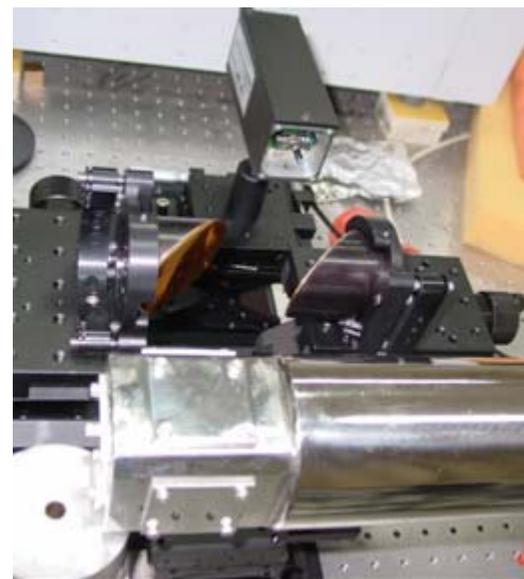


焦热电探测器

聚乙烯窗片

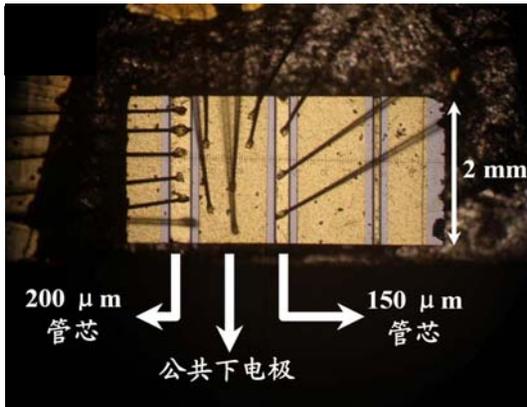
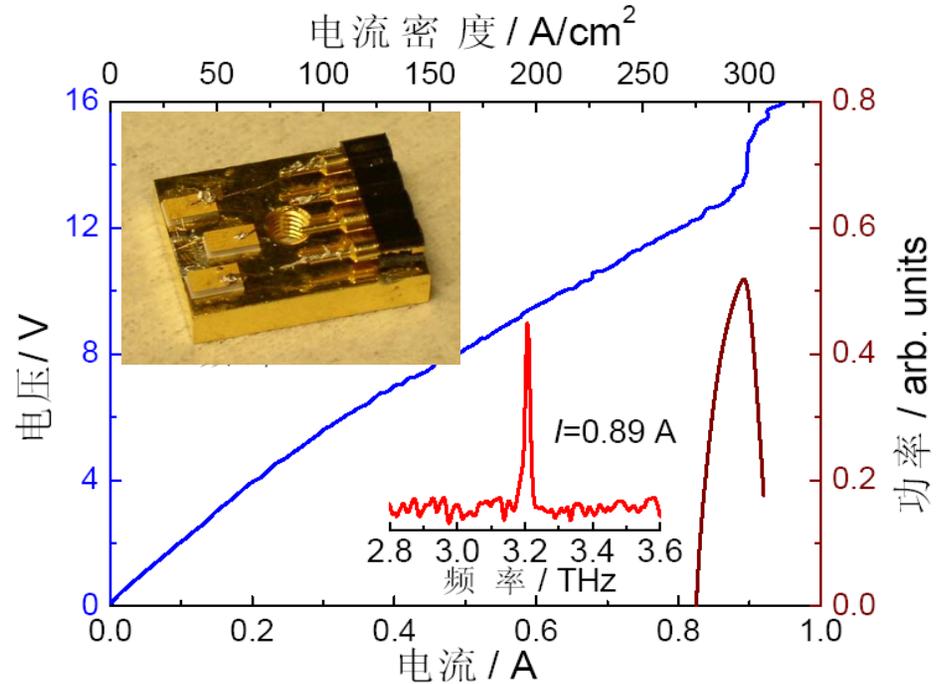
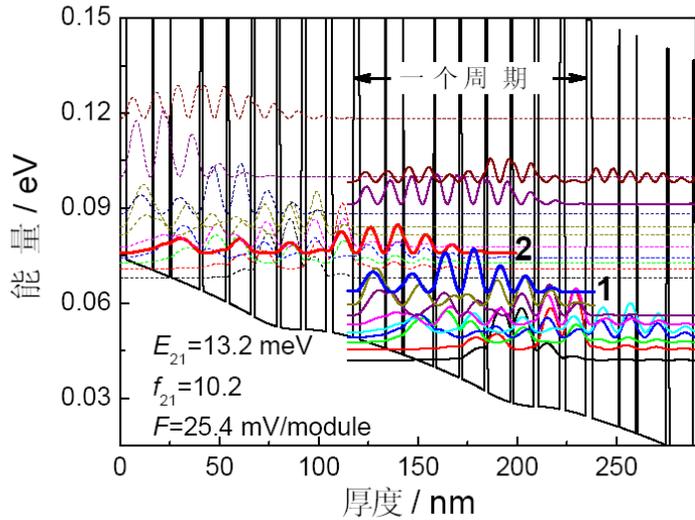


THzQCL



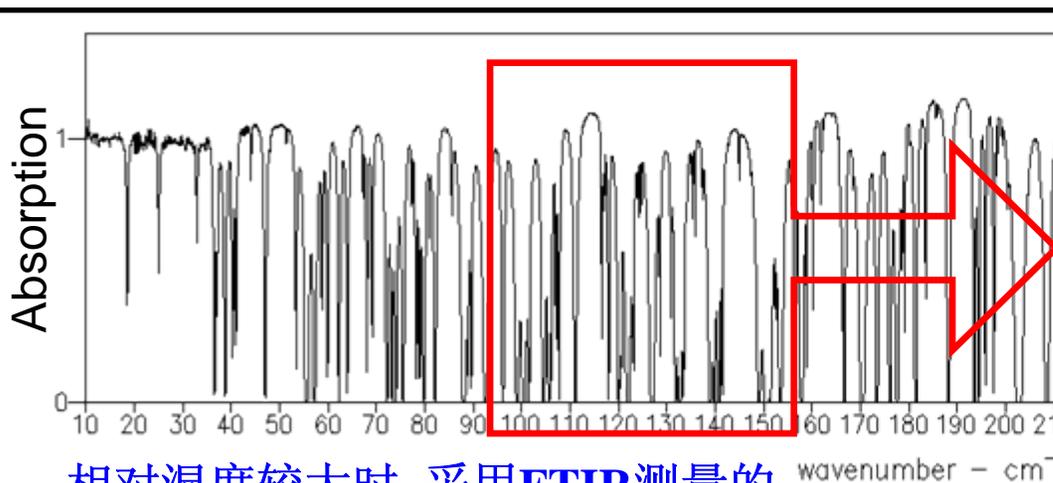
# 3.2 THz QCL研制

有源区：束缚态到连续态跃迁设计  
波导：半绝缘等离子波导

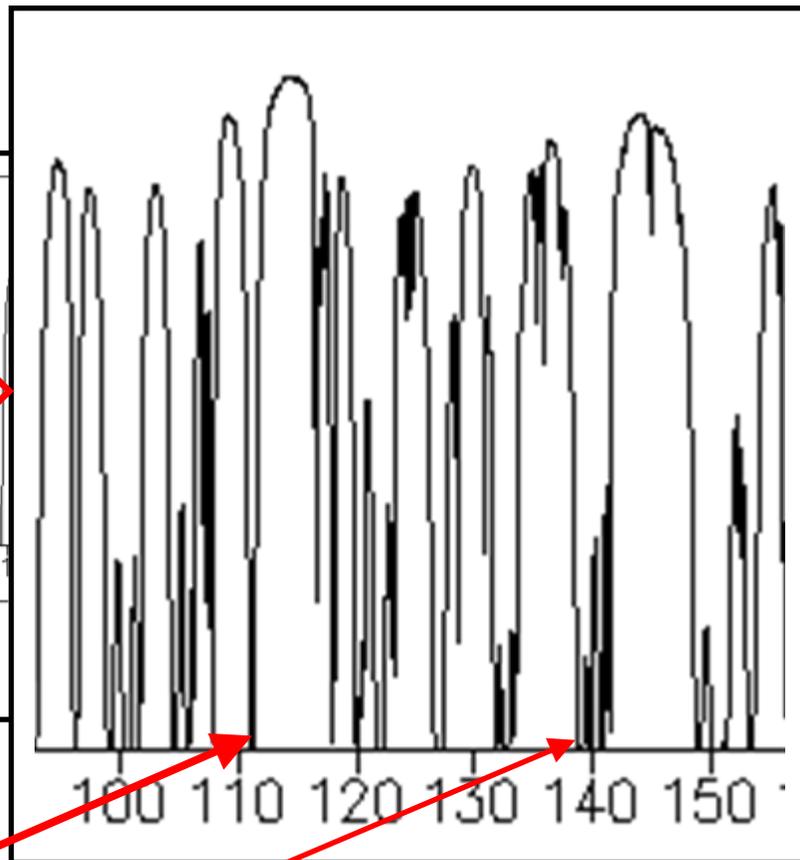


**Lasing at 3.2 THz in pulsed mode**  
**Pulse width: 3  $\mu\text{s}$ , repetition rate: 1 kHz;**  
**Measured at 10 K**  
**Device size: 150  $\mu\text{m}$   $\times$  2 mm**

# THz 频段大气窗口



相对湿度较大时, 采用FTIR测量的  
大气距离为 10 cm 的透射谱结果



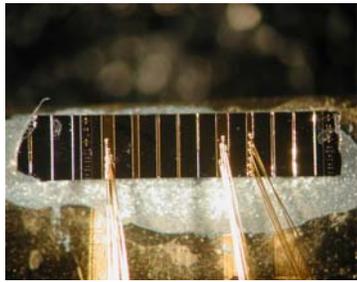
2007年自主生长的  
材料所制作器  
件的激射频率

**3.39 THz**  
**(113 cm<sup>-1</sup>)**

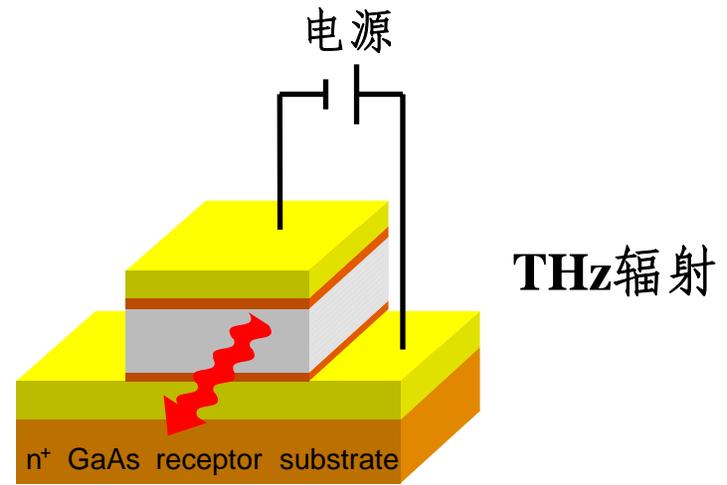
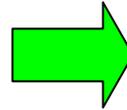
**4.1 THz**  
**(138 cm<sup>-1</sup>)**

2008年以THz频  
段为载波的无线  
通信实验中所采  
用的频点

# 通信用4.1THzQCL



THzQCL器件



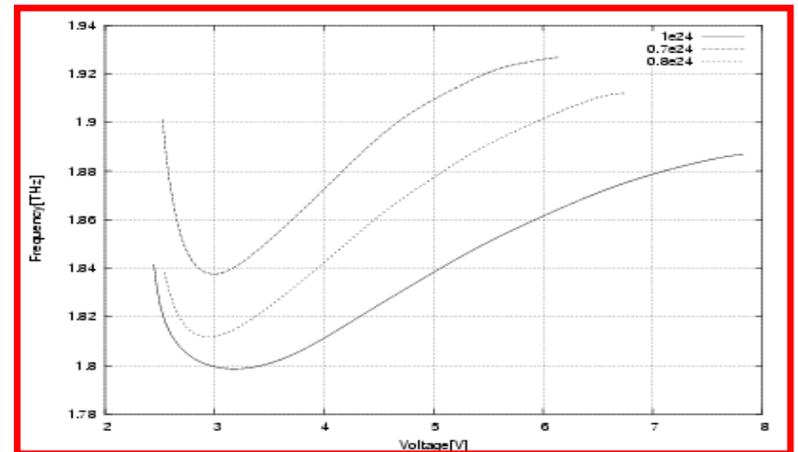
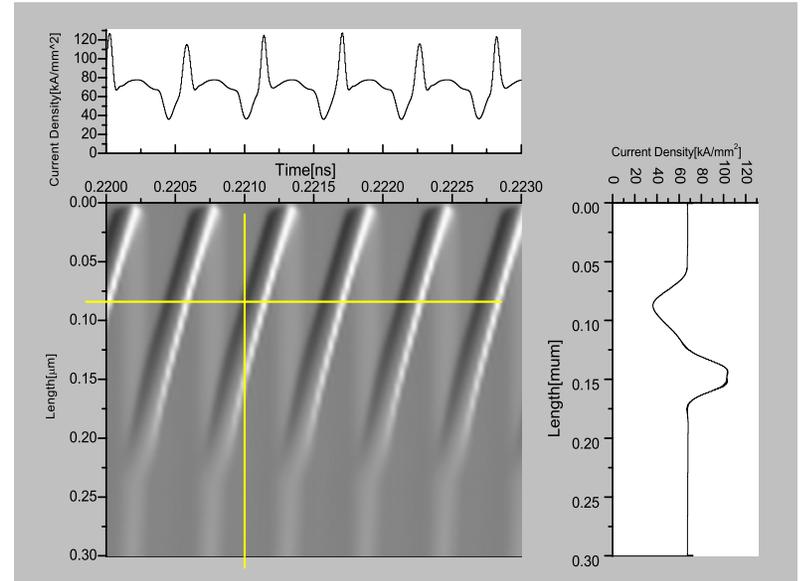
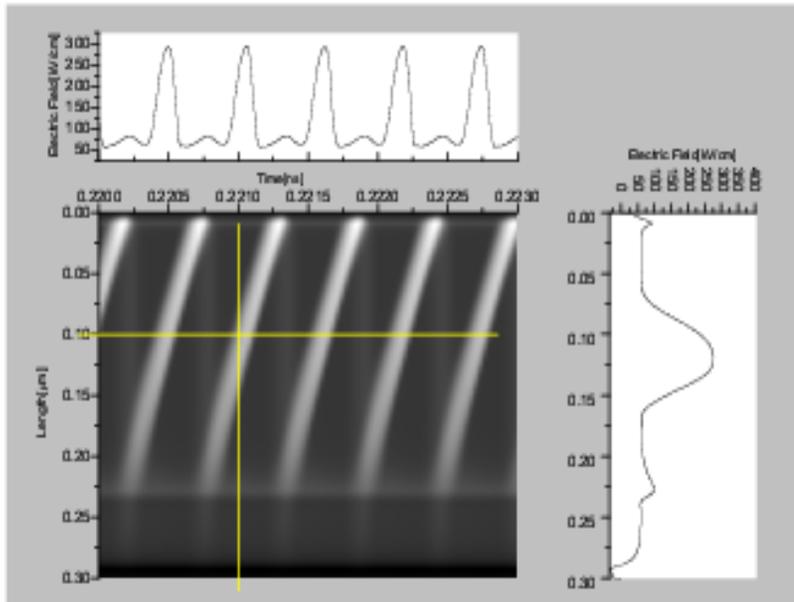
工作示意图

- 温度: ~100K (p), 40K (cw)
- 功率: ~10mW
- 频率: 4.1 THz
- 寿命长, 稳定性高
- 需要的制冷功耗: 5-12 W

# GaN NEM THz振荡器

基于Gamma带内反射点THz振荡器。突破了传统的Gunn振荡器频率难以提高的困难。

J. T. Lv & J. C. CAO, *Semicon. Sci. & Tech.* 19, 451 (2004).



一、 **THz**探测器与物理

二、 **THz**激光器与物理

三、 **THz**通信初步



# THz 波通信的特点

## 具有其它频段光通信的优点

- 带宽宽
- 高信噪比
- 天线小
- 定向性好
- 散射小
- 安全性高

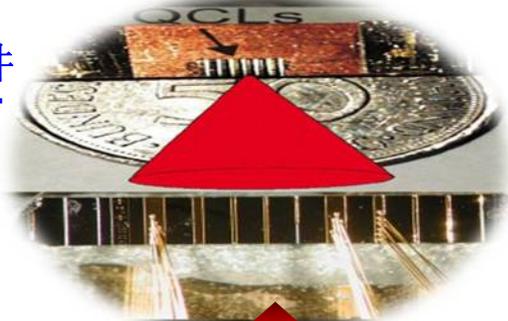
## 在安全保密通信方面

- 对于空间通信，大气可作为天然屏障，通信过程难以侦测
- 对于地面短距离通信，水气吸收严重，中远程探测极难实现
- 作为新兴技术，可消除在信息接收、发送和监测的盲区

# THz通信—大容量、高速的需求



THz波器件  
BW ~ 1 T



毫米波器件  
BW ~ 50 G

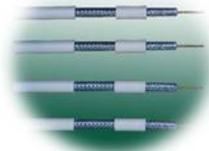
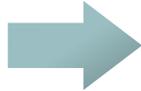


电话线  
BW ~ 50 k

同轴电缆  
BW ~ 10 M

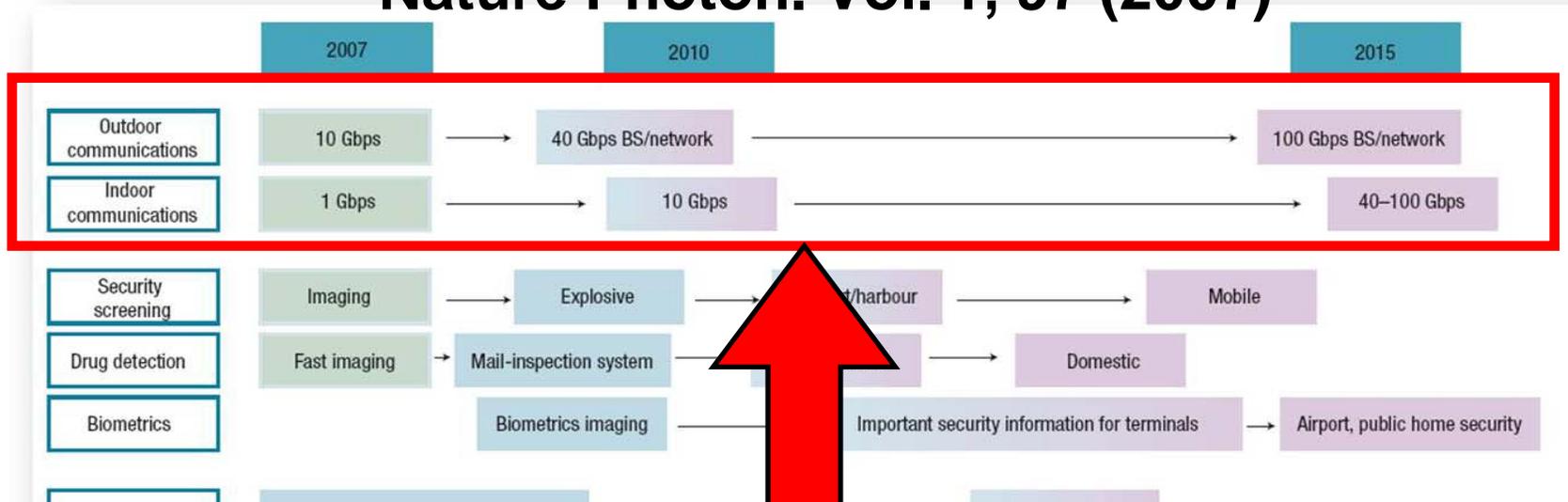
光纤  
BW ~ 100 M

射频器件  
BW ~ 5 G

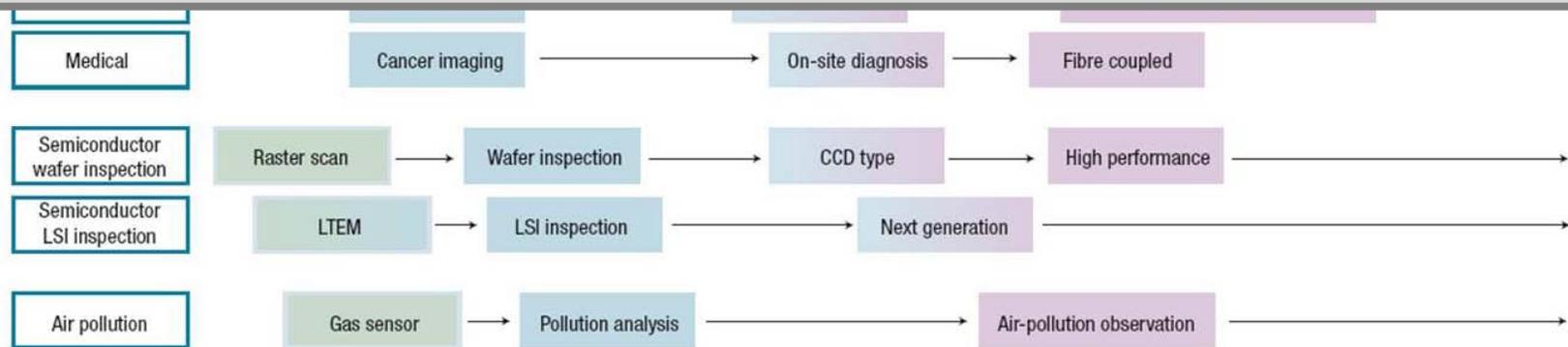


# 预期的THz通信发展路线图

Nature Photon. Vol. 1, 97 (2007)



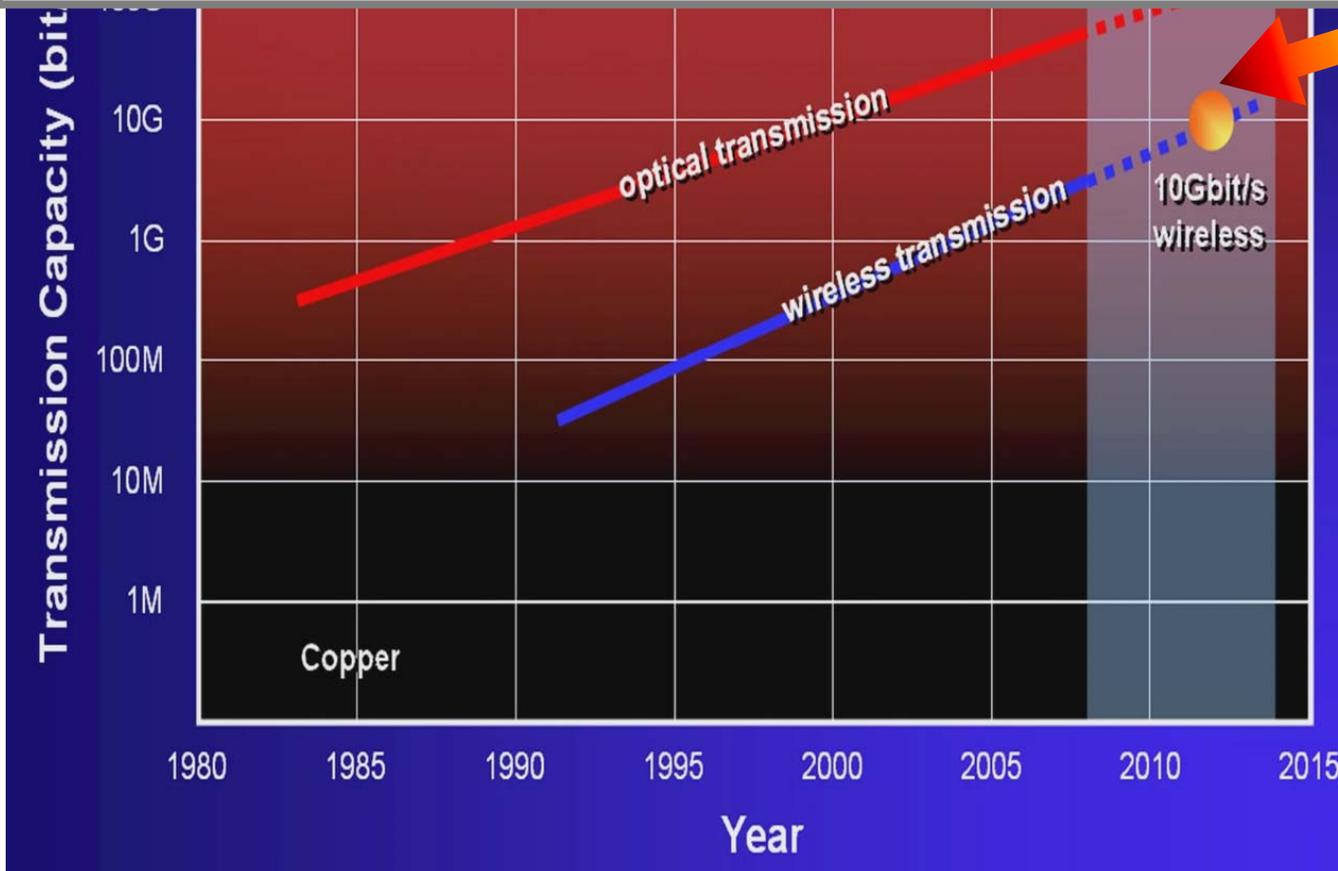
2015年，THz室内和室外通信将分别达到  
**100 Gbps** 和 **40 Gbps** 以上的通信速率



# 欧洲 IPHOBAC 的预计

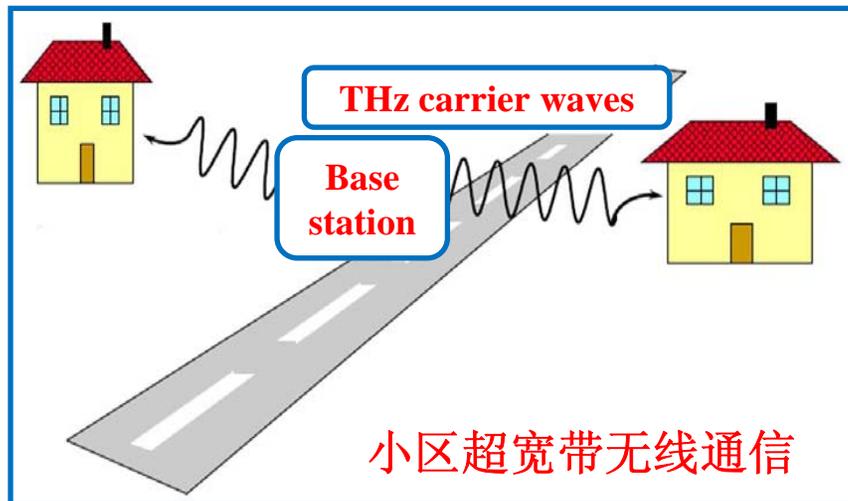
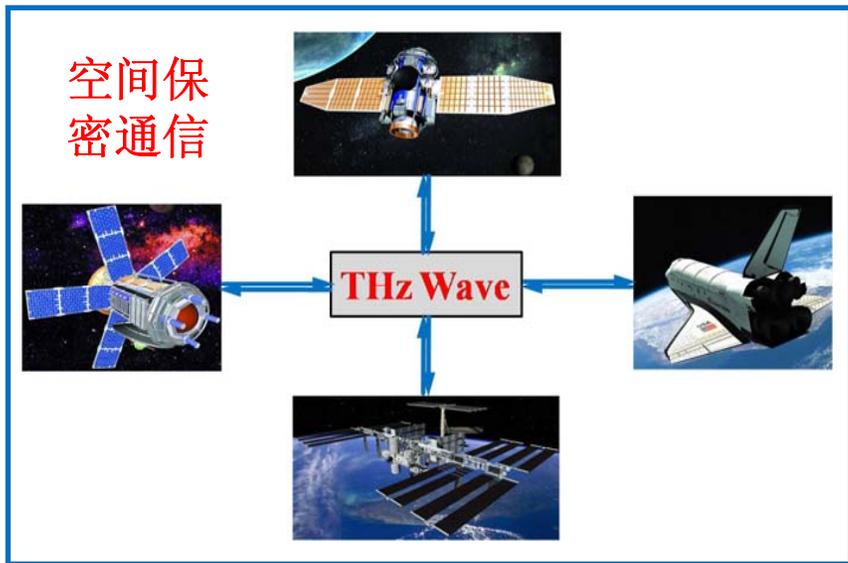
未来高速率 (百 Gbps) 信号传输迫切需要  
**THz 器件及 THz 通信系统的快速发展**

**2012年,**  
**商用无线**  
**通信系统**  
**的通信速**  
**率有望到**  
**10 Gbps**

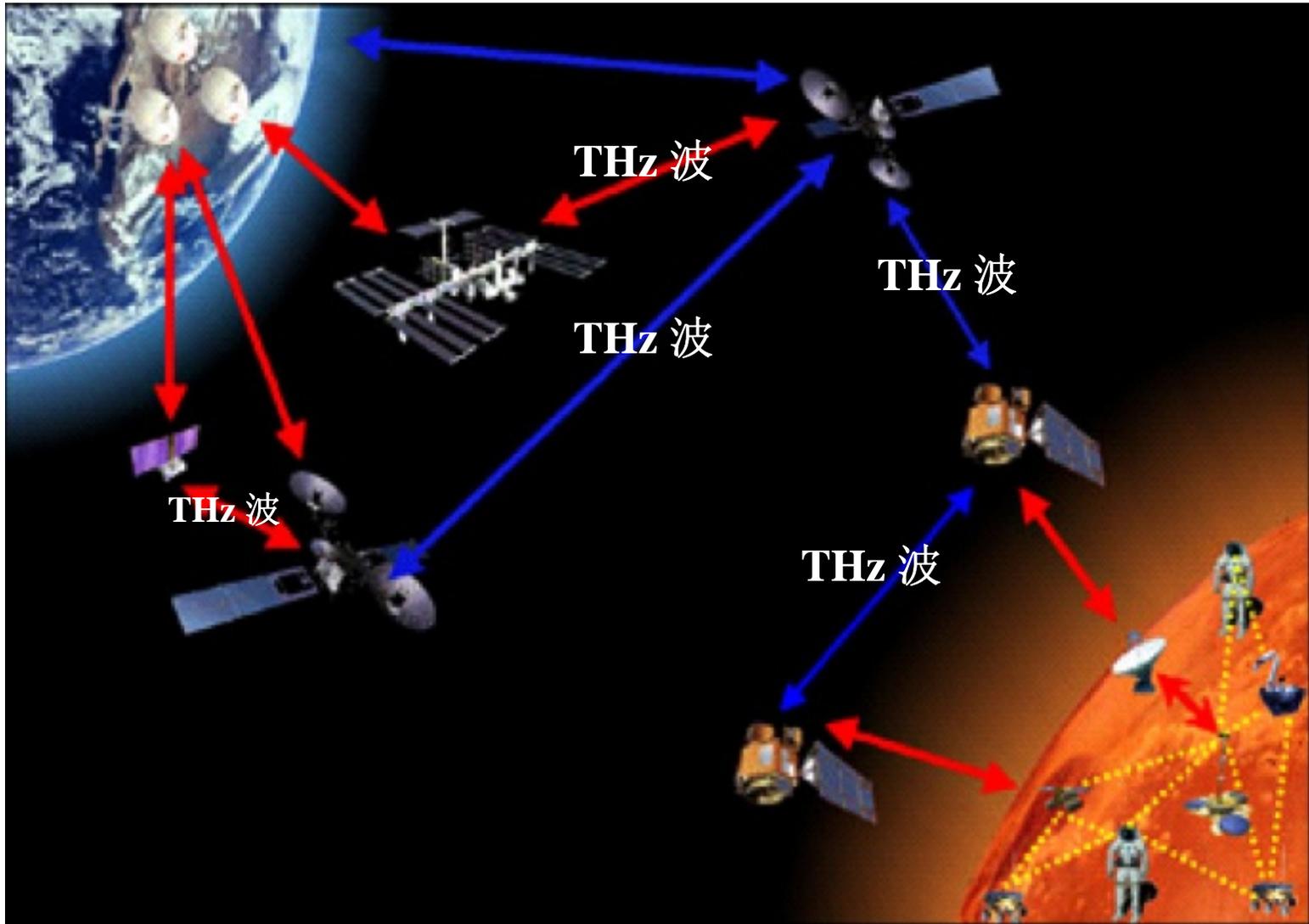


IPHOBAC是欧洲一项始于2006年(为期三年)的计划, 该计划整合了光子学和无线电技术来制作高于 30 GHz 的毫米波光子 (mmWP) 器件。该计划汇集了6个国家的11个研究机构。

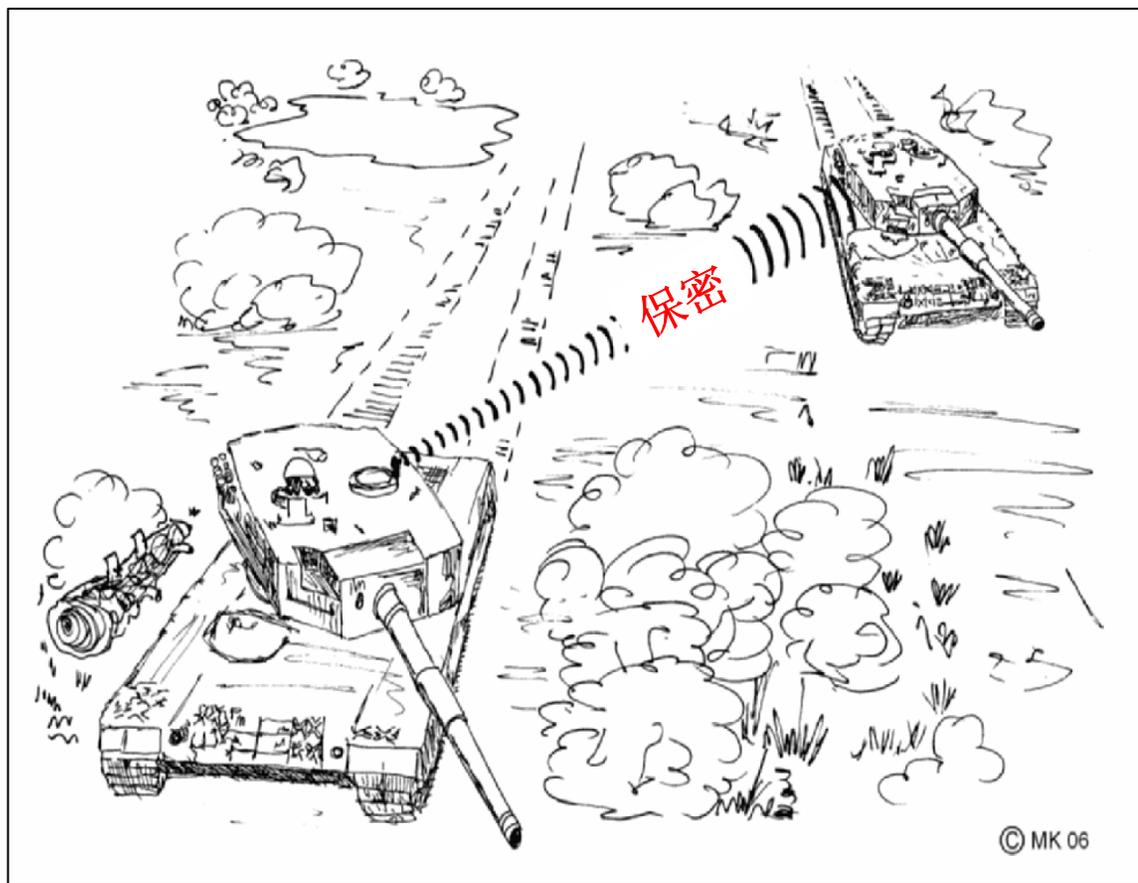
# THz 通信的主要应用领域



# 空间保密通信

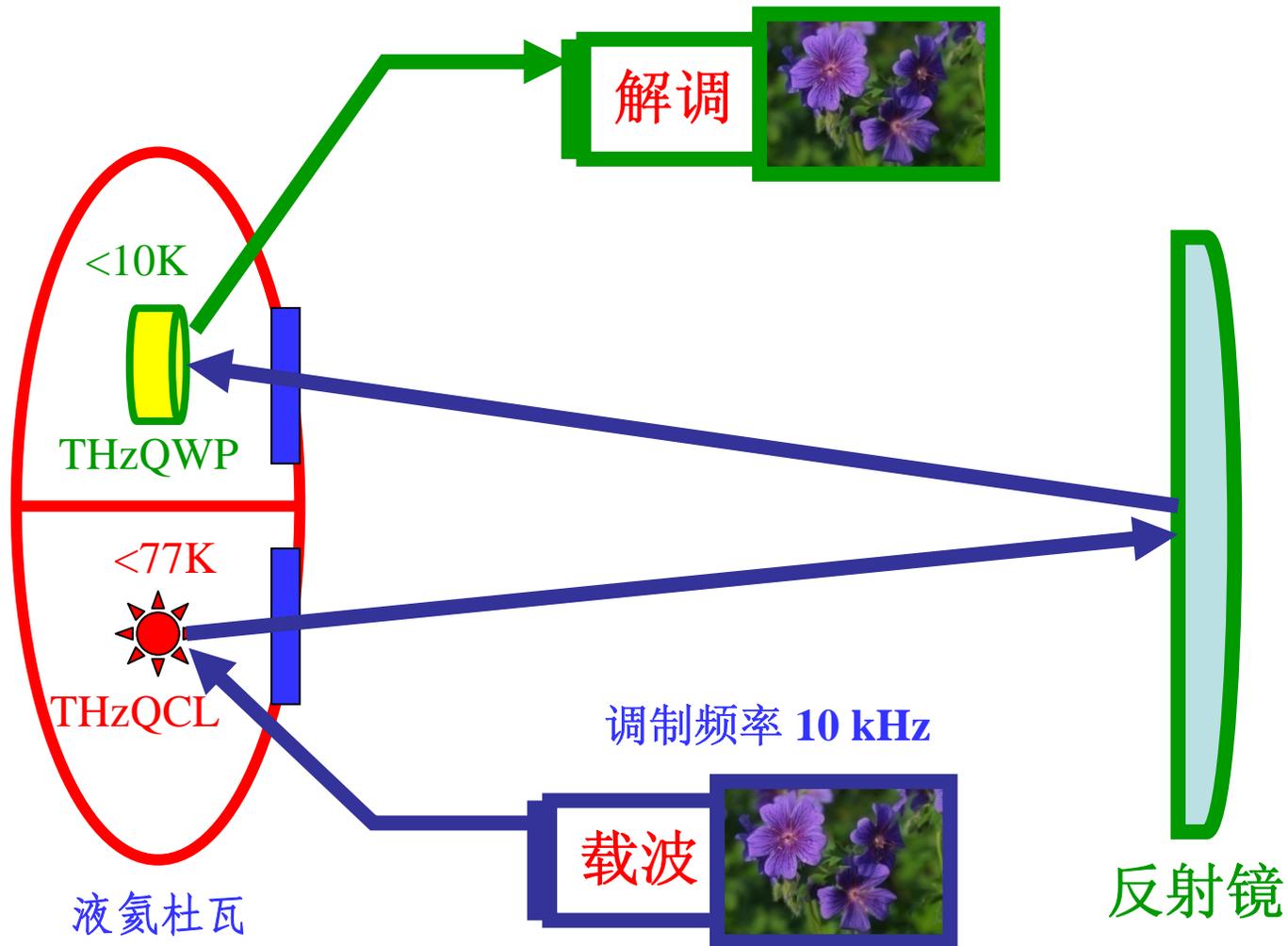


# 战地短距离保密通信的需要



随着信息时代的发展，信息战成为主导，而实时的战地短距离通信可以为作战指挥提供方便。目前THz频段的战地短距离通信尚未应用，由于大气对THz波吸收严重，对此频段通信过程的监听更是难上加难，从而使THz短距离无线通信倍受保密通信发展的青睐。

# 空间THz波通信实验方案示意图

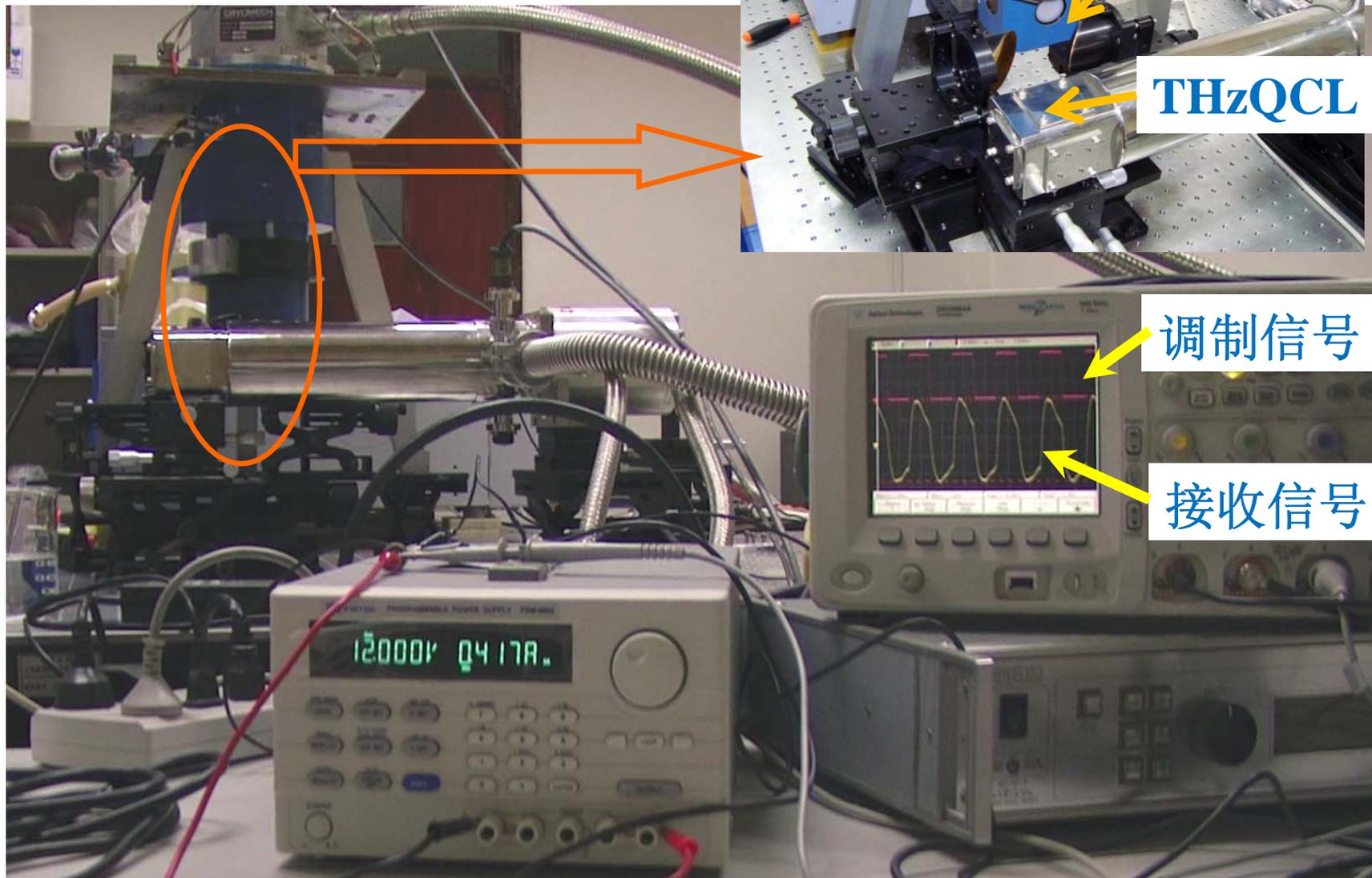


# THz通信演示—中科院上海微系统所(2008)

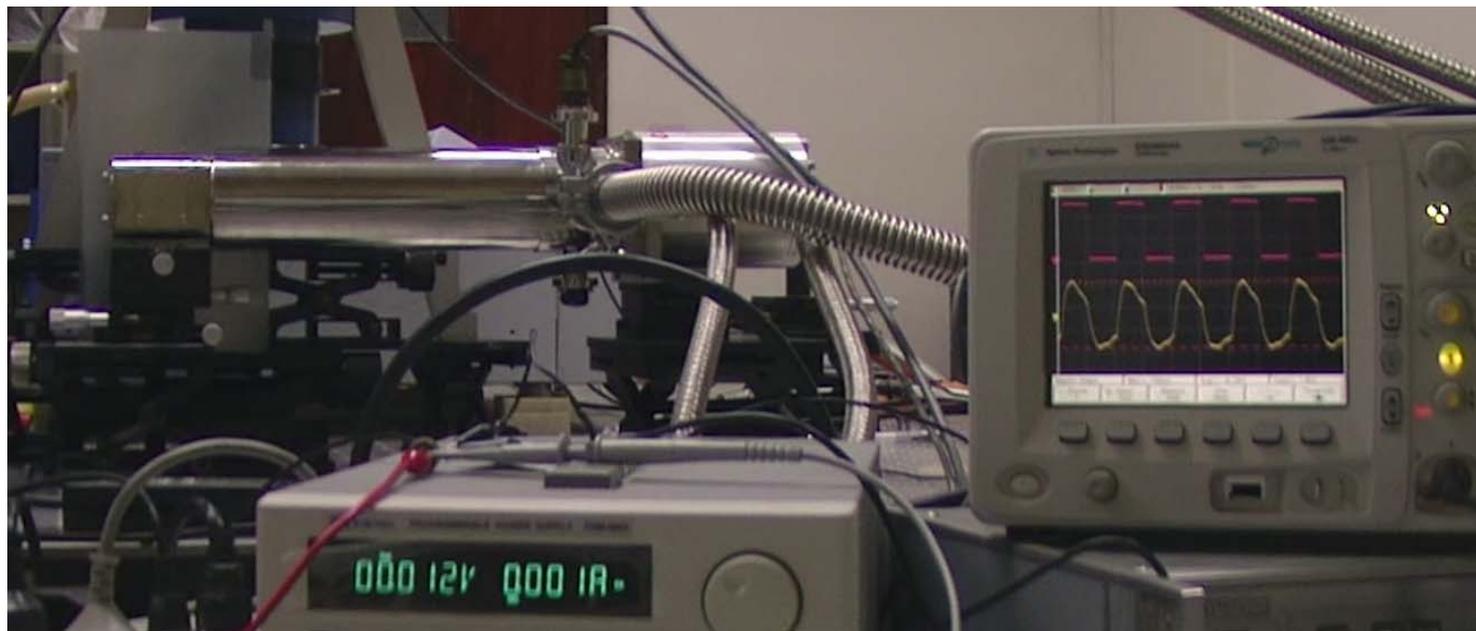
- 由 THzQCL 发射激光，按照调幅的原理直接调制QCL的发射光强
- 由探测器来探测QCL发射光强的变化，从而提取所需传输的信号，实现由THz激光作为载波的信号传输
- 通信频点：4.1 THz



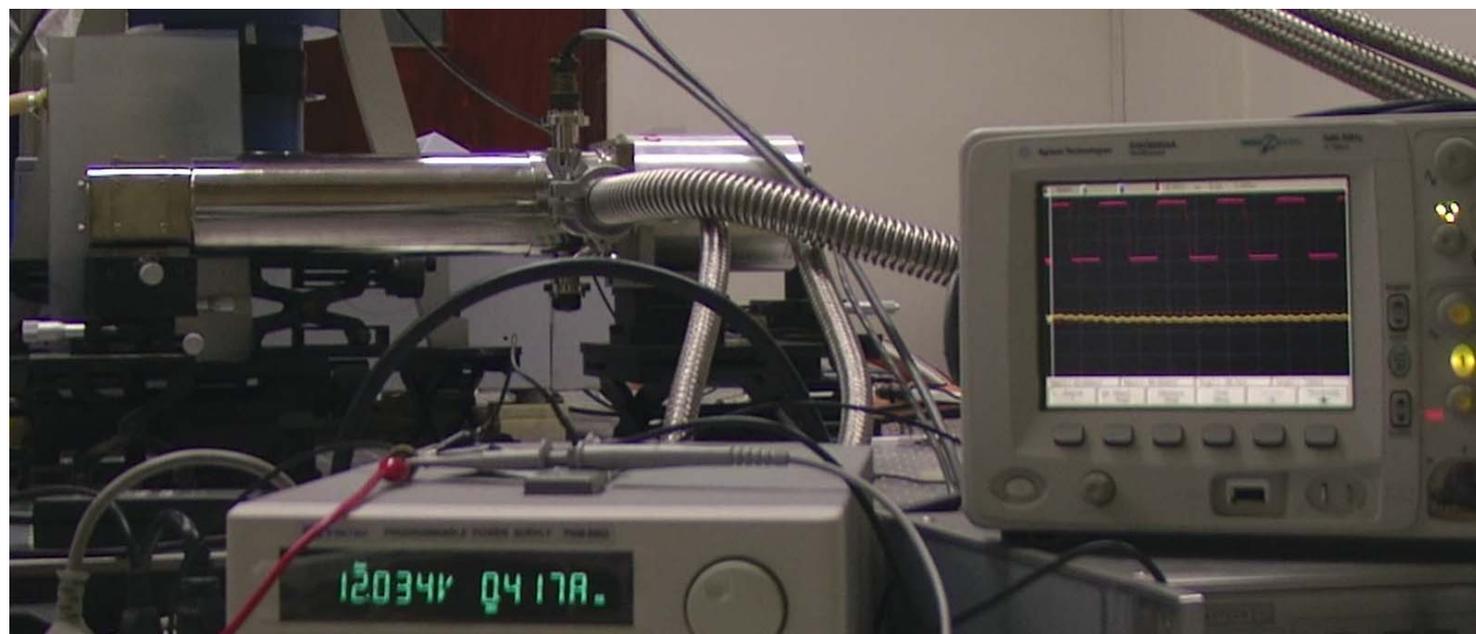
# THz通信演示系统2008 (中科院上海微系统所)



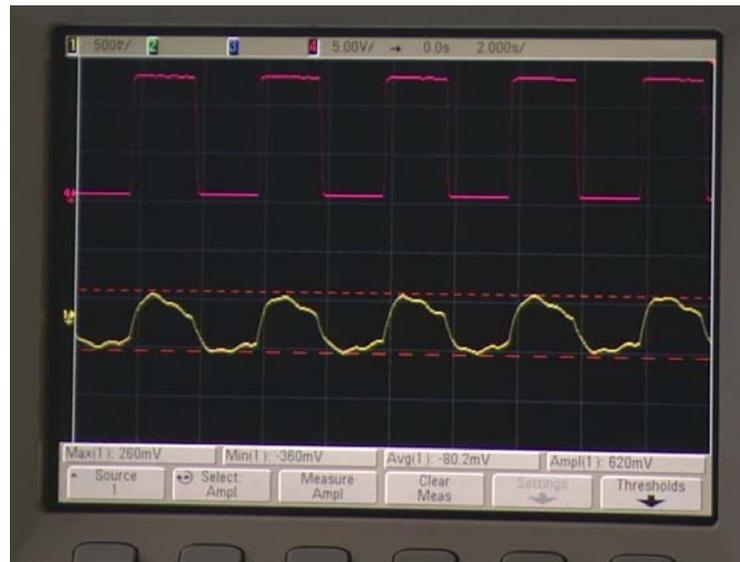
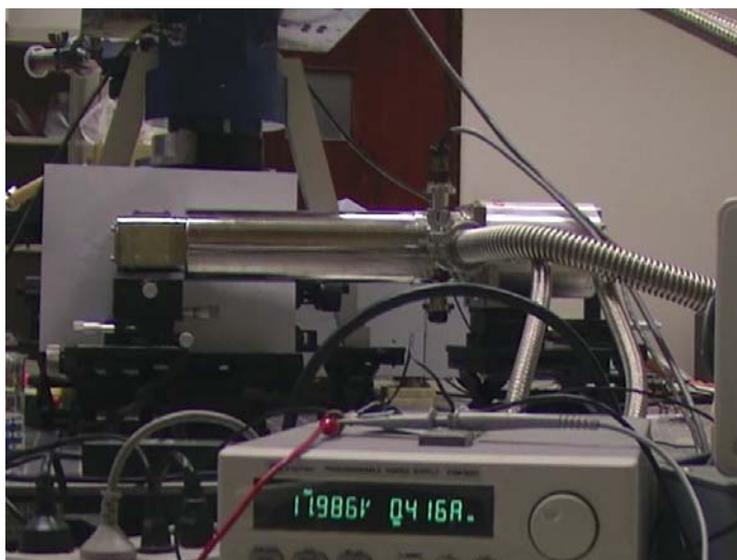
双层聚乙烯板遮挡



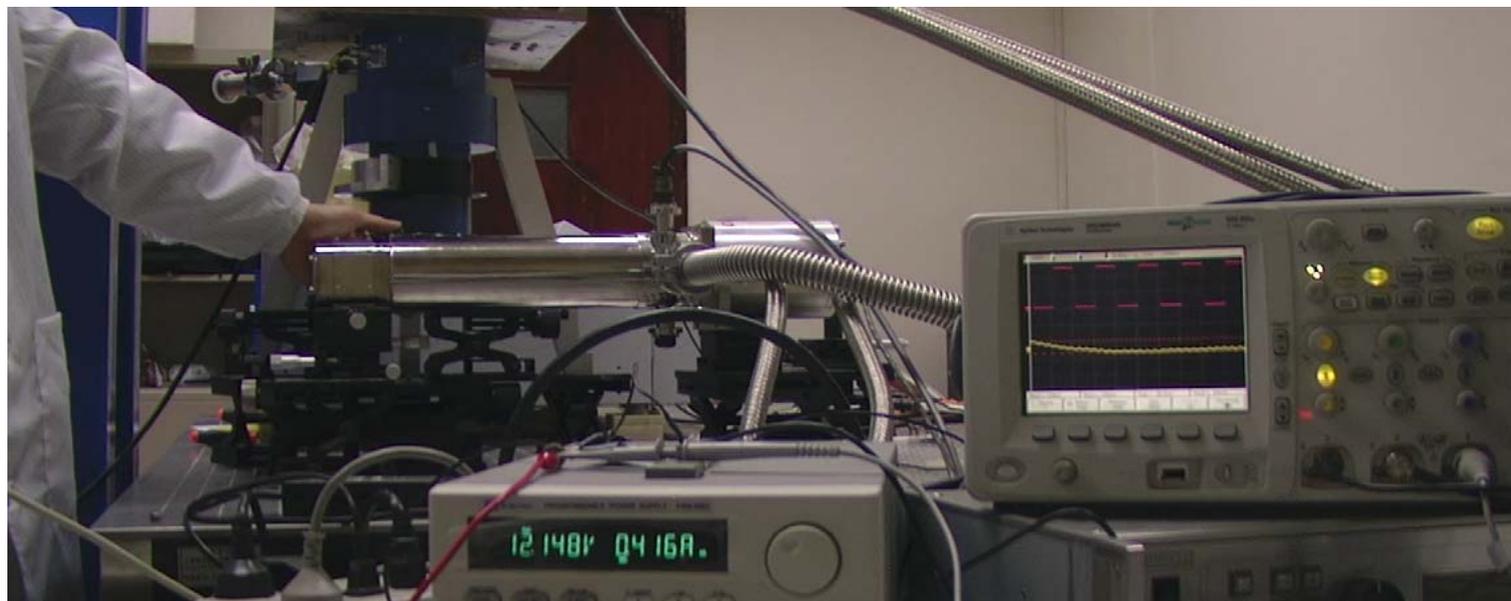
双层聚乙烯板夹水层后遮挡



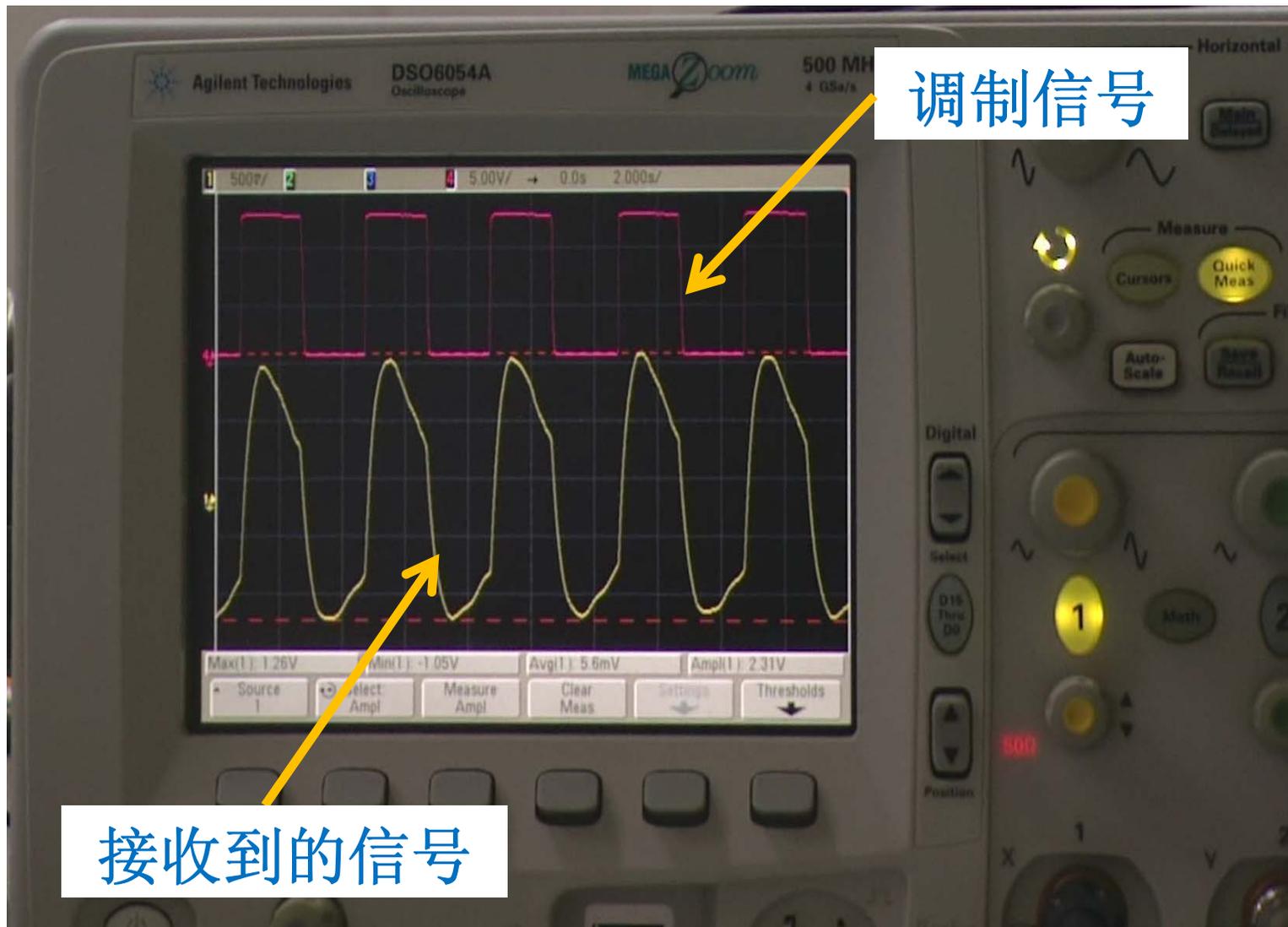
A4  
纸  
遮  
挡



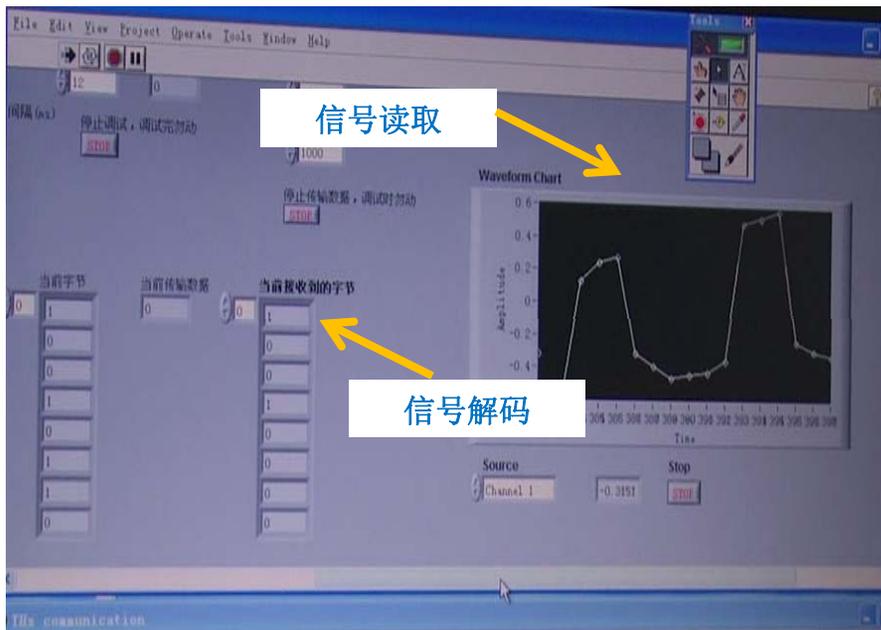
手  
遮  
挡



# 调制驱动电源的信号和THzQWP接收到的信号



# 文件传输过程中的软件控制



左图：THzQWP探测到被调制的THz光之后，会产生光电流的变化，提取上述变化后我们将电流信号转换成电压信号，并用控制软件结合示波器进行读取，最后将读取值解调为二进制编码，将被传输信号还原，完成信号的传输。

右图：被传输文件内容及通过THz无线传输后的接收到的文件



# 小结

- THz研究在近些年内取得了巨大进展
- 我国在THzQCL研制方面取得进展，并形成了研究队伍合理、设备齐全的研究平台
- THz空间通信有望实现信息的快速、大容量和高保密传输，进行THz通信试验有望在这一领域实现跨越式发展
- THz空间通信方案与短波长光通信方案类似，可以借鉴已有技术，但在关键器件研制、特定制冷系统研制等方面具有挑战性和重要意义

请指正

谢谢

