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基于太赫兹量子阱光电探测器的成像技术研究进展

符张龙 [1]，李锐志 [1,2]，李弘义 [1,2]，邱付成 [1,2]，谭智勇 [1]，邵棣祥 [1,2]，张真真 [1]，顾亮亮 [3]，万文坚 [1]，曹俊诚 [1*]

[1] 中国科学院上海微系统与信息技术研究所太赫兹固态技术重点实验室，上海 200050；
[2] 中国科学院大学，北京 100049；
[3] 上海理工大学光电信息与计算机学院，上海 200093

摘要：太赫兹(THz)波对非极性材料有较好的穿透性，对生物医学组织无电离效应，因而非常适合无损检测、生物医学成像等应用。THz 量子阱光电探测器(THz QWPs)具有响应速度快、响应率高、噪声等效功率低、体积小的特点。相较于其他探测器，THz QWPs 作为成像系统接收器时，系统具有成像分辨率高、成像速度快、成像信噪比高、结构紧凑等优势。本文综述了基于 THz QWPs 的成像研究进展，并对成像系统核心指标的影响因素进行了分析和总结。采用更稳定的装置固定 THz QWPs，提升器件响应速度、探测灵敏度、阵列规模，可以有效提升系统各项核心性能。

关键词：太赫兹；量子阱；光电探测器；成像

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Research progress of imaging technology based on terahertz quantum well photodetector

Fu Zhanglong[1], Li Ruizhi[1,2], Li Hongyi[1,2], Qiu Fucheng[1,2], Tan Zhiyong[1], Shao Dixiang[1,2], Zhang Zhenzhen[1], Gu Liangliang[3], Wan Wenjian[1], Cao Juncheng[1*]

[1] Key Laboratory of Terahertz Solid-State Technology, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China;
[2] University of Chinese Academy of Science, Beijing 100049, China;
[3] School of Optical-Electrical and Computer Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China

Abstract: Terahertz (THz) waves have a good transmissivity through non-polar materials, and have no ionization effects on biomedical tissues. Therefore, it is ideal for the applications such as non-destructive testing and biomedical imaging. The imaging system based on THz quantum well photodetectors (THz QWPs) has higher imaging

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作者简介：符张龙(1987-)，男，硕士，助理研究员，上海市青年科技英才杨帆计划入选者，主要从事太赫兹探测器及其应用方面的研究。E-mail：zlfu@mail.sim.ac.cn
通信作者：曹俊诚(1967-)，男，博士，研究员，博士生导师，国家杰出青年基金获得者，上海市自然科学牡丹奖获得者，上海市优秀学科带头人。主要从事太赫兹物理、器件及通信与成像应用方面的研究。E-mail：jccao@mail.sim.ac.cn

resolution, faster imaging speed, higher signal-to-noise ratio, and more compact structure than the imaging systems based on other detectors, as the THz QWPs have fast response, high responsivity, low noise equivalent power, and tiny size. This paper reviews the research progress of the imaging technology based on THz QWPs. And the factors affecting the core indicators of the imaging system are analyzed and summarized. Using more stable fixtures to mount the THz QWPs, improving the device response speed, detection sensitivity, array size, can improve the key performance of imaging systems effectively.

Keywords: terahertz; quantum well; photodetectors; imaging

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1 引 言

太赫兹波(Terahertz，THz)成像技术是 THz 领域中最重要的研究方向之一[1]。自 1995 年，Hu 等人首次实现 THz 成像演示实验[2]，该技术得到了各国研究人员广泛的关注和重视，并且在天文观测、人体安检、医学成像、无损检测等多个应用领域均取得了重要进展[3-7]。随着这些应用的发展，对探测器提出了等效噪声功率小、响应速度快、紧凑性好、廉价等要求。

THz 量子阱探测器(quantum well photodetectors，QWP)是基于 GaAs/(Al,Ga)As 量子阱子带跃迁的一种器件(器件如图 1(a)所示)。器件工作原理如图 1(b)所示，太赫兹光照之前，电子被束缚在量子阱中，当太赫兹光照射 THz QWP 时，束缚态电子吸收光子并被激发到第一激发态，成为连续态的自由电子，自由电子运动到达接触层形成光电流，从而实现对太赫兹光的探测。自 2004 年，加拿大国家实验室的刘惠春与中国科学院上海微系统所的曹俊诚等人联合研制出第一个 THz QWP[8]以来，国内外多个研究小组对该器件的材料设计[9-13]、响应率[14-23]、响应速度[24-26]、暗电流[27-30]、光电流谱[31-35]、电磁调谐[30,36-39]等进行了系统研究。经过系列优化，目前峰值频率设计误差在 10%以内[9]，最优响应率 5.5 A/W[23]，最快响应速度 6.2 GHz[24]，最佳噪声等效功率：$\sim10^{-13}$ W/Hz$^{0.5}$[30]，光谱峰值 4.5 THz~6.5 THz 连续可调[30]。相比其他典型 THz 探测器(表 1 所示)而言，THz QWPs 兼具噪声等效功率小、响应速度快、全固态、器件工艺成熟等优点，非常适合用于 THz 成像。

2 基于 THz QWP 的成像技术

目前，已经有不少基于 THz QWP 的成像演示实验，按照光机扫描方式主要分为：二维栅格扫描成像、三维断层扫描成像、二维阿基米德螺线扫描成像、共聚焦扫描成像、无像素成像等几种主要方式。我们将对上述成像方式进行逐一介绍。

2.1 二维栅格扫描成像

2.1.1 透射成像

2012 年，周涛等人设计了一种 THz QWP 作为成像探测器，商用标准黑体作为辐射源，移动成像物体进行二维栅格扫描的透射成像系统(如图 2(a)所示)[40]。THz QWP 峰值频点：3.2 THz，峰值响应率：0.5 A/W，比探测率：10^{11} cm·Hz$^{0.5}$/W，工作温度~3.4 K；标准黑体辐射温度：300 K~473 K，辐射孔径：60 mm。如图 2(b)所示，使用该系统对一个隐藏信封中的钥匙进行成像(成像区域：25 mm×45 mm，扫描步进：1 mm，

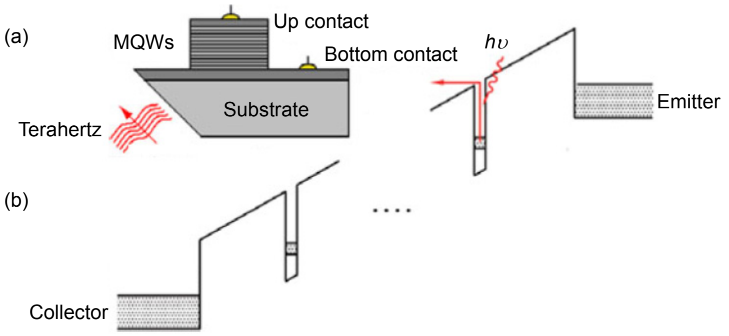

图 1 (a) 器件结构；(b) n 型 45°面耦合 THz QWP 的能带结构图[10]

Fig. 1 (a) Device schematic; (b) Band profile of an n-type GaAs/(Al,Ga)As 45° facet coupled THz QWP[10]

表 1 常见 THz 探测器的主要特性比较。参考文献[10]更新数据

Table 1 Comparison of main features of common terahertz detectors. Updated with ref.[10]

Detectors	NEP/(pW/Hz$^{0.5}$)	Response time/s	Frequency/THz
Golay cell, typical	~140	>0.03	0.04~20
VO$_x$ bolometers	~40	>0.01	1.0~10
LiTiO$_3$ pyroelectric detectors	~400	>0.01	0.2~30
Schottky barrier diodes	~100	10^{-10}	0.1~10
Superconducting hot electron bolometers	0.1 times the quantum limited	~2×10^{-10}	0.1~10
Si bolometers	~0.1	>0.025	0.15~20
Pair-breaking detectors	Close to quantum limit	~2×10^{-10}	<2.0
Glow discharge detector	12600	~10^{-3}	0.1~0.25
Terahertz quantum well photodetector	~0.1	~10^{-10}	1.5~7.6 & 8.8~20.5

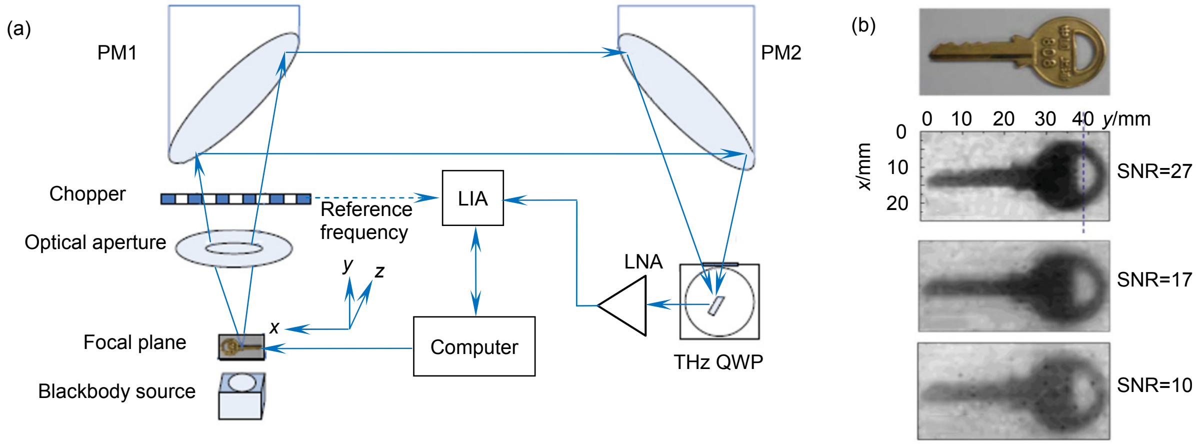

图 2 (a) THz 栅格扫描透射成像装置(使用黑体作为辐射源);

(b) 对比隐藏的钥匙可见光图像(最上面)与信噪比分别为 27、17、10(从上至下)时的 THz 成像图[40]

Fig. 2 (a) Setup of the THz raster scanning transmission imaging system (with a blackbody as the source); (b) Comparison of visible image (top) and THz images for the hidden metal key with different SNR: 27, 17, and 10 (from top to bottom)[40]

总像素：1125，成像分辨率：1 mm~1.2 mm，成像时间：30 min)，当黑体温度分别为 473 K，423 K，373 K 时得到信噪比分别为 27，17，10。该实验是首个基于 THz QWP 的成像演示，证明了基于 THz QWP 的成像方法是可行的。

2013 年，谭智勇等人设计了一种 THz QWP 作为成像探测器，THz 量子级联激光器(quantum cascade lasers, QCL)作为辐射源，移动成像物体进行二维栅格扫描的透射成像系统(如图 3(a)所示)[41]。THz QWP 性能与图 2 中一致；THz QCL 激射频点：3.9 THz，焦点光斑尺寸：0.625 mm(横轴)/0.813 mm(纵轴)。如图 3(b)对一张 100 元人民币的水印区域进行成像，成像结果如图 3(c)所示，成像区域：33 mm×52 mm，扫描步进：0.5 mm，总像素：7035，成像分辨率：0.5 mm，信噪比：~100，成像时间：180 min。该实验是首个基于 THz QWP 与 THz QCL 的联动成像演示，证明了基于 THz QWP 成像时，使用匹配的大功率高质量光源将大幅提升成像信噪比和分辨率。

2.1.2 反射成像

2014 年，谭智勇等人设计了一种 THz QWP 作为成像探测器，THz 量子级联激光器(QCL)作为辐射源，移动成像物体进行二维栅格扫描的反射成像系统(如图 4(a)所示)[42]。THz QWP 性能与图 2(a)中一致；THz QCL 激射频点：3.9 THz，焦点光斑尺寸：0.6 mm(横轴)/0.59 mm(纵轴)。如图 4(b)对一个闪存的表面进行成像，成像结果如图 4(c)所示，成像区域：38 mm×20 mm，扫描步进：0.4 mm，总像素：4896，成像分辨率：0.4 mm，成像时间：90 min。该实验证明了基于 THz QWP 成像时，可以得到较高分辨率的成像结果。

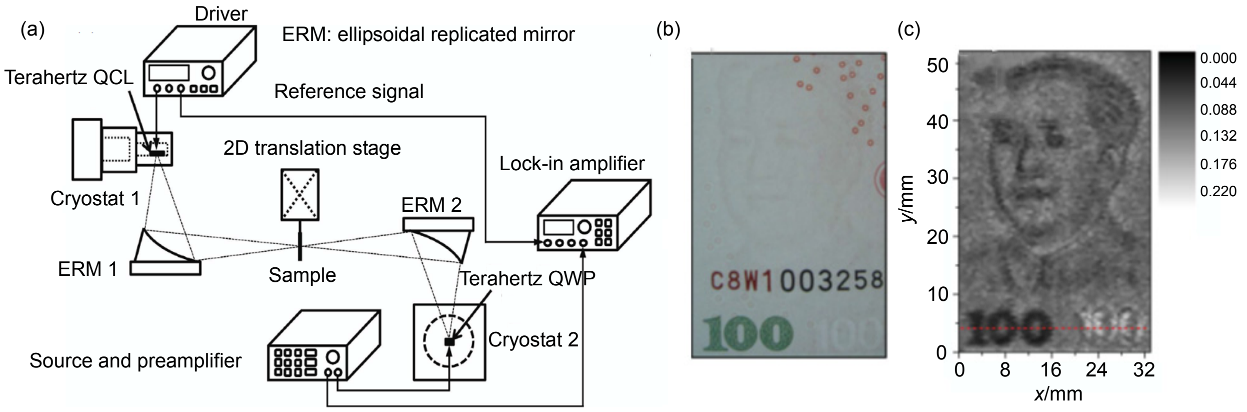

图 3 (a) THz 栅格扫描透射成像装置(使用 THz QCL 作为辐射源);
(b)，(c) 纸币水印区域的可见光成像图(b)与 THz 成像图(c)[41]

Fig. 3 (a) Setup of the THz raster scanning transmission imaging system (with a THz QCL as the source);
(b), (c) Visible (b) and THz images (c) of the watermark region of a paper money[41]

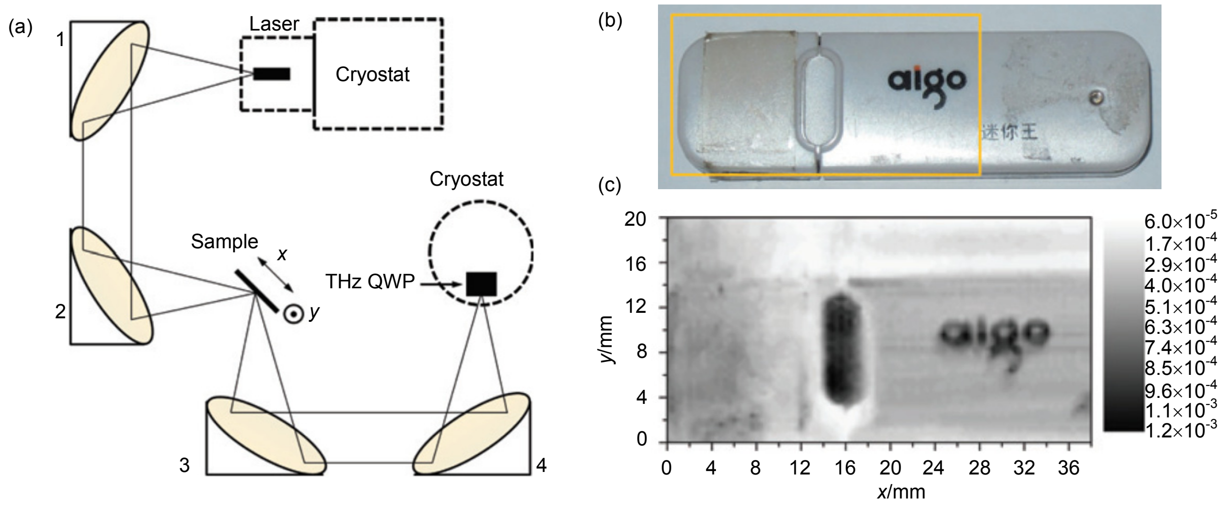

图 4 (a) THz 栅格扫描反射成像装置(样品移动); (b)，(c) 闪存表面的可见光成像图(b)与 THz 成像图(c)[42]

Fig. 4 (a) Setup of the THz raster scanning reflection imaging system (with sample moving);
(b), (c) Visible (b) and THz images (c) of the surface of flash disk[42]

2019 年，邱付成等人设计了一种 THz QWP 作为成像探测器，THz 量子级联激光器(QCL)作为辐射源，移动反射镜进行二维栅格扫描的反射成像系统(如图 5(a)所示)[43]。THz QWP 峰值频点：4.2 THz，峰值响应率：0.5 A/W，噪声等效功率：4×10^{-13} W/Hz$^{0.5}$，工作温度 5 K；THz QCL 激射频点：4.3 THz。对如图 5(b)中国科学院成立 40 周年纪念徽章和图 5(d)聚氨酯材料内壁的水滴分别进行成像，THz 成像结果分别如图 5(c)和如图 5(e)所示。两图成像区域：20 mm×30 mm，扫描步进：0.2 mm，总像素：15000，成像分辨率：0.52 mm，成像时间：~60 min。该实验表明，基于 THz QWP 进行反射扫描成像时，可以通过移动三维反射镜组实现对静止物体的 THz 成像。

2.2 三维断层扫描成像

2012 年，周涛等人设计了一种 THz QWP 作为成像探测器，THz 量子级联激光器(QCL)作为辐射源，旋转和双向平移成像物体进行三维断层扫描的成像系统(如图 6(a)所示)[44]。其中，THz QWP 峰值频点：3.2 THz，峰值响应率：0.5 A/W，比探测率：10^{11} cm·Hz$^{0.5}$/W，工作温度~3.4 K 与图 2(a)中一致；THz QCL 激射频点：3.9 THz，焦点光斑直径：1.5 mm。如图 6(b)对一个放在白色塑料盒子里的离轴抛面镜进行成像，成像区域：85 mm×85 mm，扫描步进：1 mm，转向步进：12°，采集层数：24 层，层间步进：1.2 mm，总采样：7225×24，信噪比：~600，成像时间：~24 h。

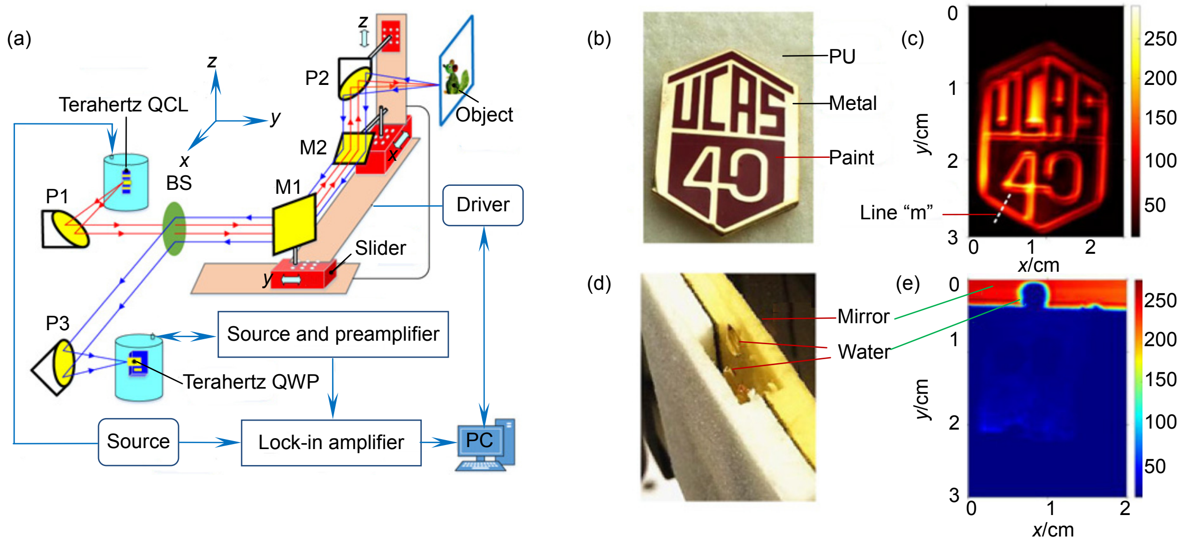

图 5　(a) THz 栅格扫描反射成像装置(反射镜移动)；(b)，(c) 中国科学院成立 40 周年纪念徽章的可见光成像图(b)与 THz 成像图(c)；(d)，(e) 聚氨酯(PU)绝缘材料内壁三滴水的可见光成像图(d)与 THz 成像图(e)[43]

Fig. 5　(a) Setup of the THz raster scanning reflection imaging system (with mirrors moving); (b), (c) Visible (b) and THz images (c) of a commemorative badge of the 40th anniversary of the University of Chinese Academy of Sciences; (d), (e) Visible (d) and THz images (e) of three drops of water covered with the polyurethane (PU) insulation materials[43]

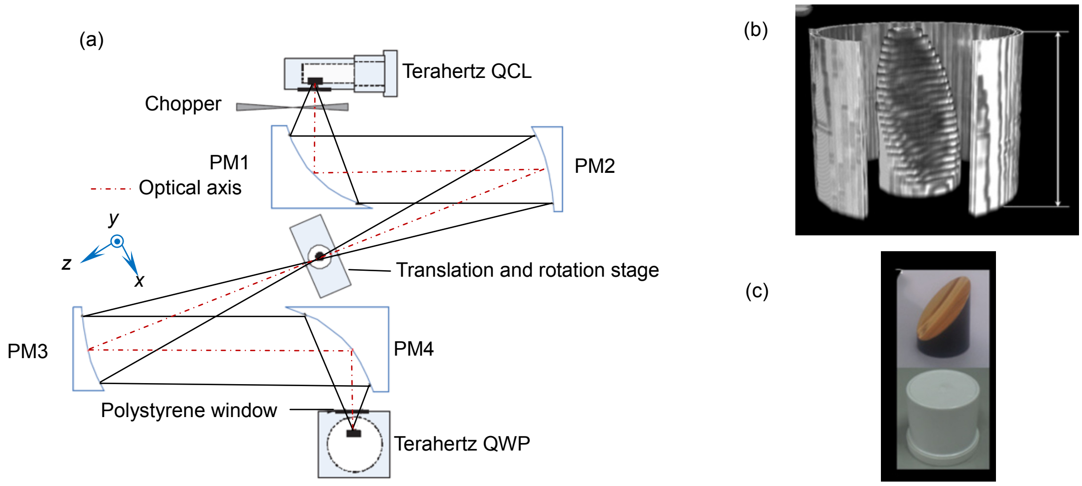

图 6　(a) THz 三维成像；(b)，(c) 离轴抛面镜的 THz 成像图(b)与 THz 成像图(c)[44]

Fig. 6　(a) Setup of the THz 3D imaging system; (b), (c) Visible (b) and THz images (c) of a off-axis parabolic mirror[44]

该实验表明，基于 THz QWP 进行三维断层扫描成像时，成像结果与实际样品在定量上吻合较好，ART 算法同样适用于 THz 波段，可在 THz 波段实现其他波段类似的断层扫描成像。

2.3　二维阿基米德螺线扫描成像

2018 年，邱付成等人设计了一种 THz QWP 作为成像探测器，THz 量子级联激光器(QCL)作为辐射源，旋转和单向平移成像物体进行二维阿基米德螺线扫描的成像系统(如图 7(a)所示)[45]。THz QWP 和 THz QCL 性能参数与图 5(a)系统中器件性能一致。对一片塑料袋遮盖一半的叶子(如图 7(b))进行 THz 成像，成像结果如图 7(c)所示；对一片聚乙烯盖子完全遮盖的叶子(如图 7(d))进行 THz 成像，成像结果如图 7(e)所示。成像区域：直径 100 mm，总像素：5000，成像分辨率：0.45 mm(横向)/0.3 mm(纵向)，成像时间：5 s。该实验表明，基于 THz QWP 进行二维阿基米德螺线扫描成像时，避免了光机扫描系统的机械停顿，大幅提升了系统成像速度。

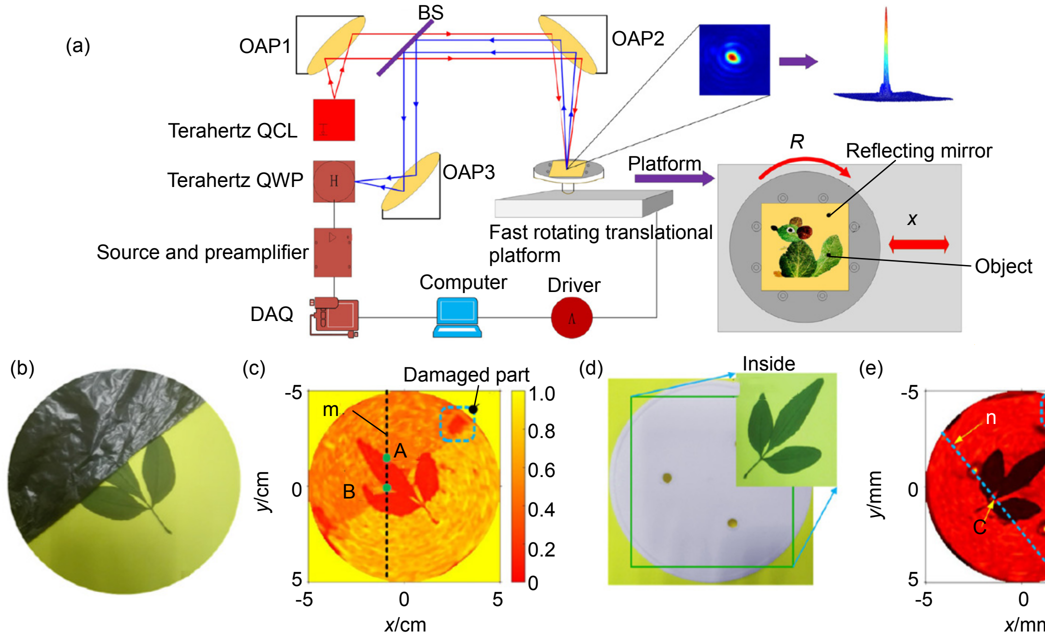

图 7 (a) THz 阿基米德螺旋线扫描成像装置; (b), (c) 塑料袋遮盖住一半叶子的可见光图(b)与 THz 成像图(c); (d), (e) 聚乙烯盖板完全遮盖叶子的可见光图(d)与 THz 成像图(e)[45]

Fig. 7 (a) Setup of the THz archimedes spiral scanning imaging system; (b), (c) Visible (b) and THz images (c) of a leaf half covered with a plastic bag; (d), (e) Visible (d) and THz images (e) of a leaf covered with a polyethylene lid[45]

2.4 共聚焦扫描成像

2019 年，邱付成等人在基于 THz QWP 作为成像探测器的二维阿基米德螺线扫描系统基础上，在光路中两处光斑焦点位置放置亚波长针孔(直径 0.2 mm)，从而同时实现共聚焦成像系统(如图 8(a)所示)[46]。THz QWP 和 THz QCL 性能参数与图 5(a)系统中器件性能一致。使用系统对图 8(b)塑料刷子、8(d)刮胡刀刀片、8(f)金属板、8(h)硬币分别进行成像，对应 THz 成像图分别为图 8(c)、8(e)、8(g)、8(i)。成像区域：直径 100 mm，成像分辨率：0.11 mm(横向)/0.32 mm(轴向)，总像素：5000，信噪比：~125，成像时间：5 s。该实验表明，基于 THz QWP 进行共聚焦二维阿基米德螺线扫描成像时，可以同时获得高扫描速度和高空间分辨率。

2.5 无像素成像

2016 年，符张龙等人研制出堆叠生长 THz QWP 和发光二极管(LED)形成的 THz 频率上转换器件(THz QWP-LED)，并使用该器件进行无像素成像[47]。45°角耦合 THz QWP-LED 成像系统如图 9(a)所示，峰值频点：5.2 THz，峰值响应率：0.22 A/W，噪声等效功率：5.2×10^{-12} W/Hz$^{0.5}$，工作温度~3.5 K；THz QCL 激射频点：4.3 THz。图 9(b)为 THz QWP-LED 对 THz QCL 不同激射功率的成像结果，成像分辨率：优于 0.05 mm，信噪比：优于 10000，成像时间：1 s。目前，该类型正入射一维及二维金属光栅耦合器件均已经实现实时成像[48]，同时二维金属光栅耦合器件可以在 10 μs 内对 THz QCL 激射光斑的快速成像，成像光斑能量为高斯分布，与较长成像时间结果基本一致。该实验表明，基于 THz QWP 的频率上转换器件具备高分辨率、高速成像能力。

3 基于 THz QWP 的成像技术

从 THz 成像技术来说，必须开发高响应率、高探测灵敏度的探测器，以达到提升成像系统信噪比的目的。基于 THz QWP 成像系统关键性能参数如表 2。

THz QWP 作为 THz 领域中紧凑、廉价、高响应率、低噪声的探测器，是适用于 THz 成像系统的理想接收器。表 2 所列成像系统中直接透射和直接反射成像系统光路简单，但是成像时间较长，而且分辨率和信噪比均较低；3D 成像系统可以得到物体 3D 信息，但是成像时间很长，而且成像分辨率和信噪比较低；阿基米德螺旋线扫描成像系统的成像时间短，但是分辨率仍然不高；共聚焦扫描成像系统的成像时间短，成像分辨率相对较高，但是成像信噪比较低；无像素成像系统，成像分辨率高，成像时间极短，而且成像信噪比高，是几种成像方式中最有前景的一种。

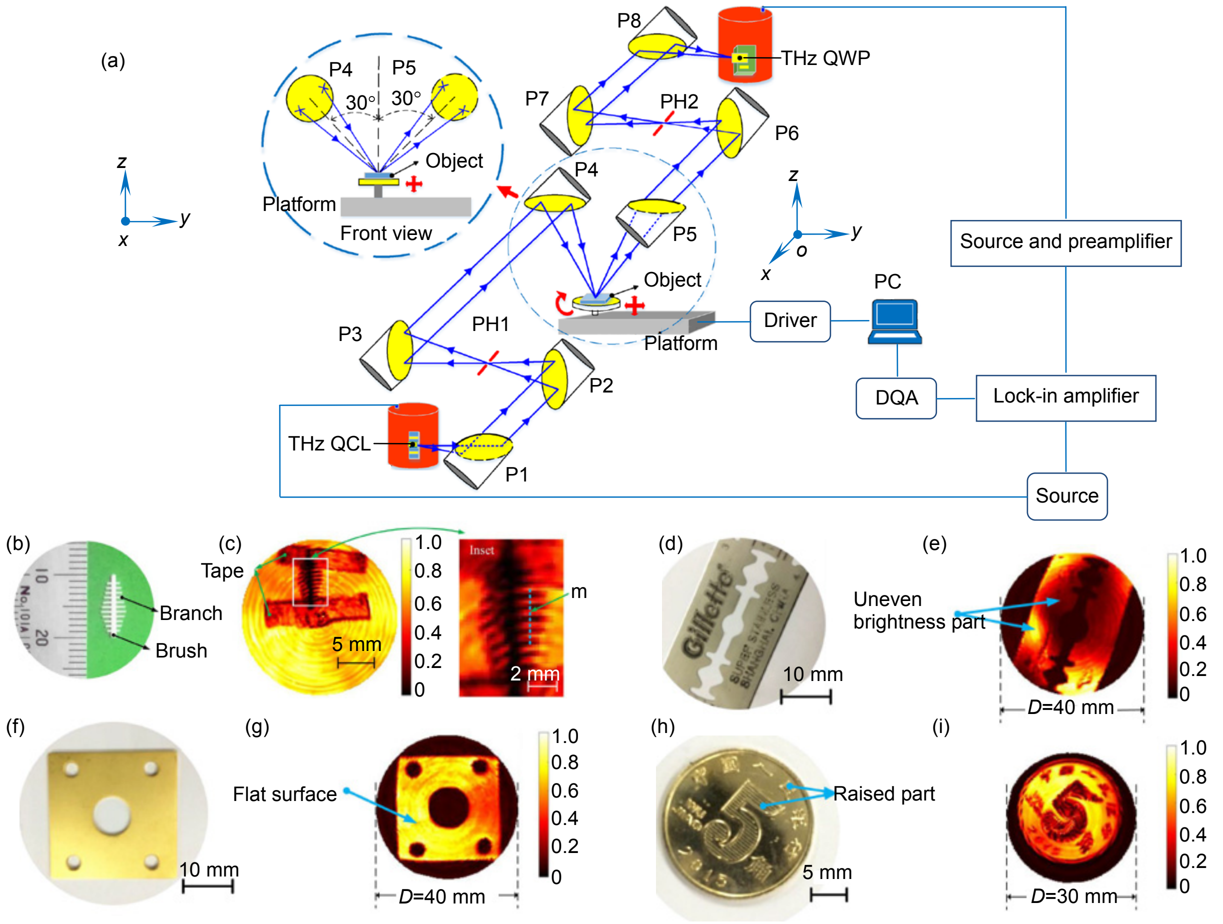

图 8 (a) THz 共聚焦扫描成像装置；(b)，(c) 塑料刷子的可见光图(b)与用胶带固定的 THz 成像图(c)；(d)，(e) 刮胡刀刀片的可见光图(d)与 THz 成像图(e)；(f)，(g) 金属板的可见光图(f)与 THz 成像图(g)；(h)，(i) 硬币的可见光图(h)与 THz 成像图(i)[46]

Fig. 8 (a) Setup of the THz confocal scanning imaging system; (b), (c) Visible image (b) of a plastic brush and THz image (c) of it fixed by the tape; (d), (e) Visible (d) and THz images (e) of a razor blade; (f), (g) Visible (f) and THz images (g) of a metal plate; (h), (i) Visible (h) and THz images (i) of a coin[46]

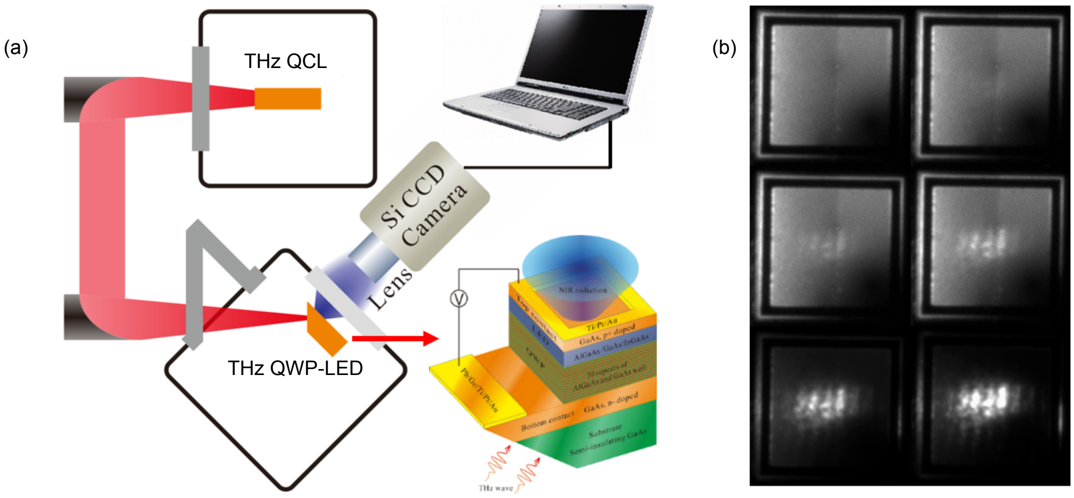

图 9 (a) THz 无像素成像装置；(b) THz QWP-LED 对不同强度的 THz QCL 激光聚焦光斑[47]

Fig. 9 (a) Setup for THz pixelless imaging system; (b) The focal laser spots of the THz QCL imaged by the THz QWP-LED[47]

表 2 基于 THz QWP 的成像系统参数

Table 2 Parameters of a imaging system based on THz QWP

Imaging type	Frequency /THz	Responsivity /(A/W)	Detection array size/pixel	Resolution/mm	Imaging time	Signal to noise ratio
Transmission imaging	3.2	0.5	1	1~1.2	0.5 h	27/17/10
	3.2	0.5	1	0.5	3 h	~100
Reflection imaging	3.2	0.5	1	~0.4	1.5 h	/
	4.2	0.5	1	0.52	1 h	/
3D imaging	3.2	0.5	1	1(*x*)/1.2(*z*)	24 h	~600
Archimedes spiral scanning imaging	4.2	0.5	1	0.45(*x*)/0.3(*y*)	5 s	/
Confocal scanning imaging	4.2	0.5	1	0.11(lateral)/0.32(axial)	5 s	~125
Pixel-less imaging	5.2	0.22	1	0.05	1 s	~10000

4 结 论

THz 成像常见核心指标为成像分辨率、成像面积、成像速度和成像信噪比等。成像分辨率受到光学衍射极限和光路限制，光学衍射极限由工作频段决定，常规方式难以优化，只有通过共聚焦等手段优化；光路对分辨率限制体现在透镜或者反射镜的色散效应、聚焦能力等。成像面积主要受限于系统光路，可以通过设计实现大面积成像，但是成像面积大时必须保证扫描系统成像镜组移动时空抖动小，重复性好，才可获得较好成像。成像速度受限于扫描机制、信号采集时间、采样点规模、探测器规模，采用无需机械停顿的可以获取更高的采样速度，但是要求探测器具有高灵敏度及高响应速度；信号采集时间受限于探测器带宽，但是同样也需要探测器具有高灵敏度，否则无法获得较高信噪比图像；采样点数量增加，采样总时长增加，成像速度越慢；探测器规模越大，相同时间采样点数越多，采样速度越快。成像信噪比主要受系统光路稳定性、光源功率稳定性、光源功率大小、探测器灵敏度等因素限制。

上述因素相互制约，必须依据实际应用需求进行一个综合权衡，来达到特定应用环境下的优化成像方案。当然，部分因素对所有核心指标提升均有帮助，如实验中采用更稳定的装置来固定光源和探测器，提升光源的出光稳定性、光束质量、功率等，提升探测器的响应速度、探测灵敏度、阵列规模等。相信随着源和探测器性能的持续提升，未来 THz 成像将变得更快(实时/超快)、更精确(高分辨率)和更简单(系统的低复杂性)，将在生物医学成像和工业成像领域发挥重要作用。

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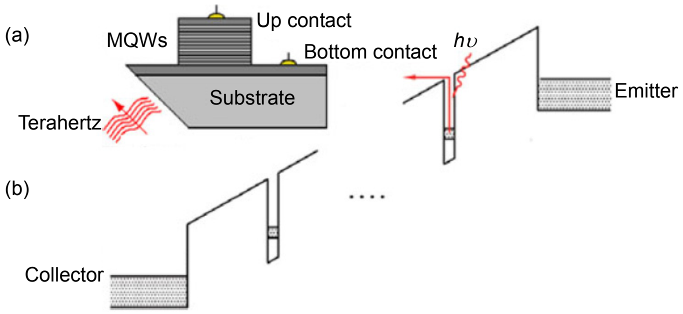
Research progress of imaging technology based on terahertz quantum well photodetector

Fu Zhanglong[1], Li Ruizhi[1,2], Li Hongyi[1,2], Qiu Fucheng[1,2], Tan Zhiyong[1], Shao Dixiang[1,2],
Zhang Zhenzhen[1], Gu Liangliang[3], Wan Wenjian[1], Cao Juncheng[1*]

[1]Key Laboratory of Terahertz Solid-State Technology, Shanghai Institute of Microsystem and Information Technology,
Chinese Academy of Sciences, Shanghai 200050, China;
[2]University of Chinese Academy of Science, Beijing 100049, China;
[3]School of Optical-Electrical and Computer Engineering, University of
Shanghai for Science and Technology, Shanghai 200093, China



(a) Device schematic; (b) Band profile of an n-type GaAs/(Al,Ga)As 45° facet coupled THz QWP

Overview: Terahertz (THz) waves have a good transmissivity on non-polar materials and no ionization effects on biomedical tissues. Therefore it is ideal for the applications such as non-destructive testing and biomedical imaging. The imaging system based on THz quantum well photodetectors (THz QWPs) has higher imaging resolution, faster imaging speed, higher signal-to-noise ratio (SNR), and more compact structure as the THz QWPs have fast response, high responsivity, low noise equivalent power, and tiny size. This paper reviews the research progress of the imaging system based on THz QWPs. The direct transmission and direct reflection imaging systems have simple light paths, and the 3D imaging system can obtain 3D information of objects. However, the imaging speed, the resolution and SNR are low. The archimedean spiral scanning imaging system progressed in imaging speed, but the resolution is still not high. The confocal scanning imaging system has a short imaging time and a relatively high imaging resolution, nevertheless, the SNR is low. The pixel-less imaging system has a diffraction-limited resolution, extremely short imaging time, and high SNR, is the most promising one above. There are some tips for system performance improvement. First, the imaging resolution can be optimized by the optical confocal methods. Second, the large imaging area can be achieved by optimized optical path design. Third, high imaging speed can be achieved with no mechanical stop scanning, multi-pixels detectors, or reducing signal acquisition time with an ultrafast detector. Forth, the SNR is mainly relying on the steady optical path, optical source power, and detector sensitivity. However, these factors are always competitive, a trade-off must be made to achieve an optimized imaging solution for a specific application. It improves the light output stability and beam quality with a more stable fixture for the source and the detector mounting. The improvement of the detector response speed, detection sensitivity, and array size are also working. It is believed that the THz imaging will become faster (real-time/ultra-fast), more accurate (higher resolution), and simpler (lower systems complexity) with these efforts. And it will play an important role in biomedical and industrial imaging in the future.

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* E-mail: jccao@mail.sim.ac.cn