

## 基于开口圆锥近场探针的太赫兹超分辨成像研究

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**摘要** 基于近场探针的太赫兹扫描成像系统能够突破衍射极限探究物质隐藏的细节,但是传统基于微纳加工工艺的近场探针存在工艺复杂、传输损耗较大的缺点。提出了一种基于空心圆波导的渐变开口圆锥形近场探针设计方法,所设计的探针能够通过圆波导实现低损耗传输,同时利用渐变开口圆锥形针尖实现亚波长聚焦。为了验证方法的可行性,采用3D打印技术对所设计的探针进行加工,然后基于高精度三维扫描平台搭建了一套0.1 THz近场扫描成像系统。实验结果表明该探针能够实现亚波长超分辨聚焦,实验结果与仿真结果一致。

**关键词** 光学设计; 3D打印; 近场探针; 太赫兹; 超分辨

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## 1 引言

太赫兹波是频率(0.1~10.0 THz)位于微波和红外之间的电磁波<sup>[1]</sup>,它具有穿透性强<sup>[2]</sup>、单光子能量低<sup>[3-4]</sup>、指纹性强<sup>[5]</sup>等优点。基于太赫兹波的成像技术在反恐安检<sup>[6]</sup>、生物医药<sup>[7]</sup>、数据通信<sup>[8]</sup>等领域中具有广泛应用。但是太赫兹波长较长,受衍射极限限制,传统太赫兹成像技术的分辨率仅在波长量级<sup>[9]</sup>,无法应用于生物细胞组织成像以及芯片内部电路成像等高精度领域,所以发展太赫兹超分辨成像显得尤为重要。根据成像距离的不同,超分辨成像可分为近场成像和远场成像。太赫兹近场成像方法可以分为近场照明和近场收集两类<sup>[10-12]</sup>,本文采用的方式就是利用物理孔径将太赫兹波聚焦在亚波长尺寸实现近场照明。

1998年,Hunsche等<sup>[13]</sup>基于亚波长孔径实现了THz高分辨率成像。他们在铝制圆锥锥尖处电镀Cr/Ni,之后将锥尖移除一部分并抛光,留下直径为100 μm的孔径,利用太赫兹波照射样品,在225 μm波长处实现了约为50 μm分辨率的成像,但是探针透射率(能量利用率)只有0.77%,损耗太大。之后2005年,Klein等<sup>[14]</sup>利用剪断的硅制针条,通过机械抛光的方式制成一个金字塔形锥尖探针,并采用超高真空电子束蒸发的方式进行定向金属沉积,对探针进行金属镀膜,最终获得1/200波长的分辨率。2009年,Berta等<sup>[15]</sup>将低损耗介质材料蓝宝石锐化成非对称的锥体探针,并将10 nm厚的钛黏合剂层、1 μm厚的银和30 nm厚的金作为保护层涂敷在探针上,获得了尺寸为50 μm×100 μm的孔径,虽然分辨率很高,但是蓝宝石

材料对太赫兹波的吸收损耗较大,影响了信噪比。2012年,Mitrofanov等<sup>[16]</sup>利用设计的双针探针制成了亚波长孔径,实现了直径小于10 μm的太赫兹聚焦,但是亚波长孔径下透射率最大为1%。2020年,Wang等<sup>[17-18]</sup>设计了一种新型探针结构,将原始矩形探针锥尖部分与空气透镜结合在一起,并且探针孔径在61.2 μm左右。为了实现这种精细结构,研究者用数控机床对聚甲基丙烯酸甲酯(PMMA)矩形探针进行精密加工,并采用了磁控溅射技术涂层,制成的探针在0.11 THz下的成像分辨率为10 μm,但是只有沿球面半径入射的波才能被聚焦,其他的都散失掉了,所以仍存在能量损耗。

2013年,Liu等<sup>[19]</sup>报道了一种基于太赫兹波段亚波长孔径的宽波段、无截止频率的圆锥形间隙探针,其是由传统锥形波导的两半组成,中间引入可变间隙,这种结构的探针可以在低于截止频率时实现太赫兹传输,且不破坏模式限制,也不会影响空间分辨率。但是为了保留大部分能量在探针端口处聚焦,间隙的宽度不能超过20 μm,间隙宽度越大,成像质量越低。所以他们采用电火花切割技术将一块3 mm厚的不锈钢板切割成两块并抛光,利用光学显微镜和亚微米精密定位平台对两半锥形探针进行边缘对准和移动处理,制作工艺和实验过程非常复杂,难度非常高。

近年来,3D打印因其灵活性强、成本低、精度高等特点,被誉为制造领域的革命性技术。本文提出了一种基于空心圆波导的圆锥渐变开口形近场探针设计方法,该方法设计的探针能够通过圆波导实现低损耗传输,同时利用渐变开口圆锥形针尖实现亚波长聚焦。

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为了验证方法的可行性,我们采用 3D 打印和金属覆膜技术对其进行加工,所加工的探针继承了间隙探针的高信噪比、宽波段、无截止频率的优点。然后,基于高精度三维扫描平台搭建了一套近场扫描成像系统,实验结果表明该探针能够实现亚波长超分辨聚焦,成像结果与仿真结果一致。

## 2 太赫兹近场探针设计以及仿真

本文设计的是基于低损耗空心圆波导和渐变开口圆锥的太赫兹超分辨近场探针,图 1 展示了整体结构设计以及参数示意图,其中  $g$  是锥尖开口缝隙宽度,  $r$  是锥尖孔半径,  $G$  是锥底开口缝隙宽度,  $L$  是整个锥体高度(长度),  $t$  是圆形波导壁厚。为了实现太赫兹亚波长聚焦,我们将锥尖处的物理孔径设计为 0.4 mm,金属空心圆波导中的传输主要模式为  $TE_{11}$  模<sup>[20]</sup>。

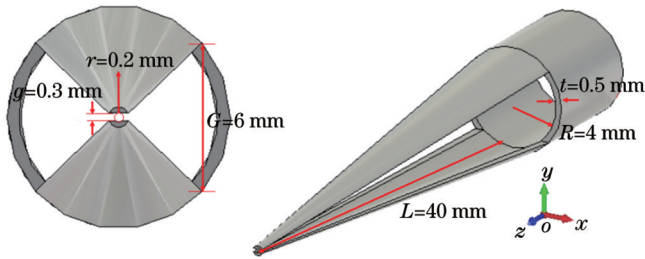


图 1 圆锥开口形探针结构示意图

Fig. 1 Schematic of conical open-mouth probe structure

横截面内半径为  $R$  的圆波导  $TM_{mn}$  模的截止波长  $\lambda_{c(TM_{mn})}$  为

$$\lambda_{c(TM_{mn})} = \frac{2\pi R}{P_{mn}}, \quad (1)$$

式中:  $P_{mn}$  为  $m$  阶贝塞尔函数的第  $n$  个根;  $m = 0, 1, 2, \dots; n = 0, 1, 2, \dots$ 。

$TE_{mn}$  模的截止波长  $\lambda_{c(TE_{mn})}$  为

$$\lambda_{c(TE_{mn})} = \frac{2\pi R}{P'_{mn}}, \quad (2)$$

式中:  $P'_{mn}$  为  $m$  阶贝塞尔函数导数的第  $n$  个根。

根据圆波导截止波长的计算公式(1)、(2)可得,当圆波导半径为 0.2 mm 时,  $TE_{11}$  主模式对应的截止波长为 0.682 mm,远小于我们的工作波长 3 mm。这意味着太赫兹波在进入锥尖之后传输会截止,无法实现锥尖处的太赫兹聚焦。所以我们在锥尖探针两侧进行开口处理,在封闭的孔中引入缝隙,这样可以使一部分电磁场泄漏到缝隙中,如图 2(a)所示,破坏了原来由最小孔径带来的太赫兹传输限制,从而支持太赫兹宽带传输<sup>[19,21]</sup>,进而可以有效避免截止波长的限制,能够极大地提高探针的空间分辨率。

设计好探针结构之后,我们用 CST Studio Suite 2019 软件对探针结构进行仿真优化,图 2 是我们的仿真结果。太赫兹波直接入射到圆波导上,向前传输的波碰到波导的金属壁后会被反射,上下表面的反射波在波导中心相互叠加形成驻波,在圆波导中以驻波的形式向前传输。进入锥形探针后,在  $x$  和  $y$  方向也有驻波出现,并且由于  $y$  方向金属板的间距逐渐减小,上下表面的反射波叠加增强,逐渐形成太赫兹聚焦<sup>[22]</sup>,如图 2 所示,最后在锥尖处形成亚波长量级的太赫兹聚焦光斑。

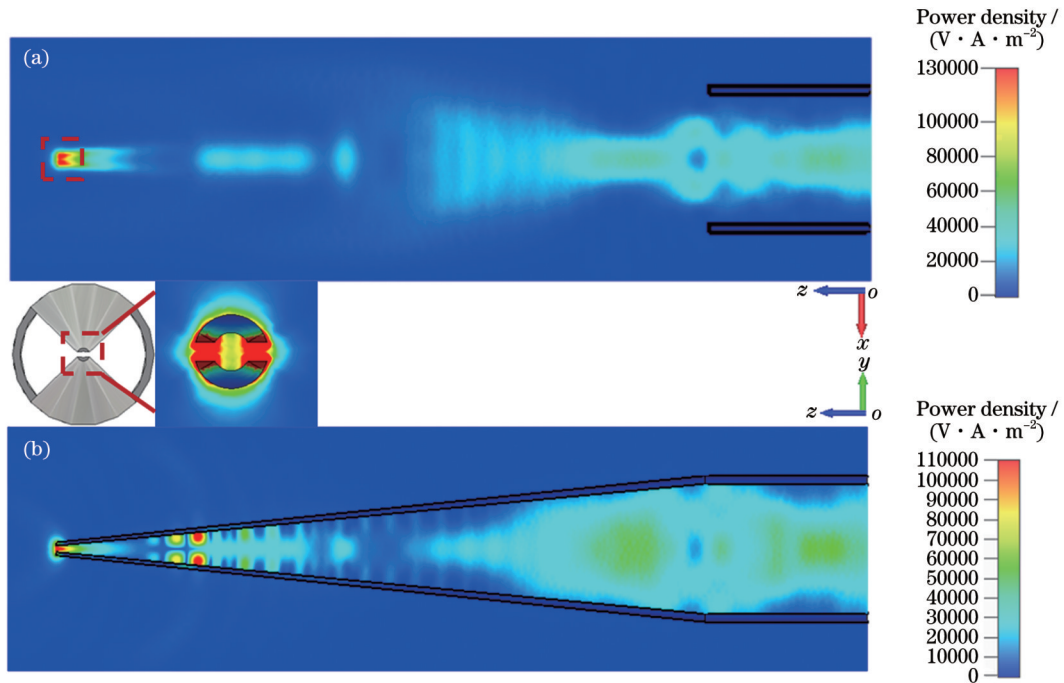


图 2 锥尖半径为 0.2 mm 的太赫兹探针的功率密度分布示意图。(a)  $x$ - $z$  平面;(b)  $y$ - $z$  平面

Fig. 2 Power density distribution diagrams of terahertz probe with tip radius of 0.2 mm. (a) In  $x$ - $z$  plane; (b) in  $y$ - $z$  plane

为了研究渐变开口圆锥形探针对太赫兹波的聚焦效果,我们对聚焦的太赫兹光斑进行了数值表征。图 3(a)是探针中心轴线  $z$  方向的功率线密度分布曲线,0 mm 处是圆波导的入射端面位置,50 mm 处是探针锥尖出射端口的的位置。然后在  $z=50$  mm 位置对  $x$  方向功率线密度分布进行曲线绘制,如图 3(b)所示,取功率线密度分布峰值的  $\frac{\sqrt{2}}{2}$  处  $x$  宽度为太赫兹光斑的聚焦宽度<sup>[17]</sup>,最后计算出  $x$  方向聚焦宽度为 0.779 mm,  $y$  方向聚焦宽度根据物理孔径大小为 0.4 mm。而我们设定的太赫兹工作频率为 0.1 THz,工作波长为 3.0 mm,理论上,圆锥形探针结构可以实现接近  $\lambda/4$  ( $\lambda$  为波长)的分辨率,从而实现超分辨成像。同时,我们发现图 3(b)的聚焦光斑具有双峰结构,这是由于探针锥尖处存在缝隙。如图 2(a)插图所示,太赫兹波在探针中向前传输时,遇到两边的缝隙,产生衍射,在左右两边

呈现强功率密度分布,相互叠加之后,产生了双峰结构。而探针锥尖半径的大小影响了双峰结构的叠加程度,半径越大,双峰结构的叠加程度越差,当锥尖半径无限减小时,双峰结构可叠加为近似单峰结构。如图 3(c)所示,可以看出,双峰结构的聚焦光斑直径(0.779 mm)大于单峰结构的聚焦光斑直径(0.617 mm),所以双峰结构会影响成像分辨率,导致成像分辨率降低。并且我们仿真了同一尺寸的探针在 0.1 THz 和 0.2 THz 处的聚焦光斑大小,结果如图 3(d)所示。两个频率处的聚焦光斑的功率线密度不同,0.2 THz 处的聚焦光斑的功率线密度约为 0.1 THz 处聚焦光斑的 6 倍;在光斑的大小方面,0.1 THz 处的聚焦光斑直径约为 0.779 mm,0.2 THz 处的聚焦光斑直径约为 0.706 mm,相差约 0.073 mm,显然 0.2 THz 处的聚焦光斑的空间分辨率较高。频率越高,聚焦光斑的直径越小,分辨率越高。

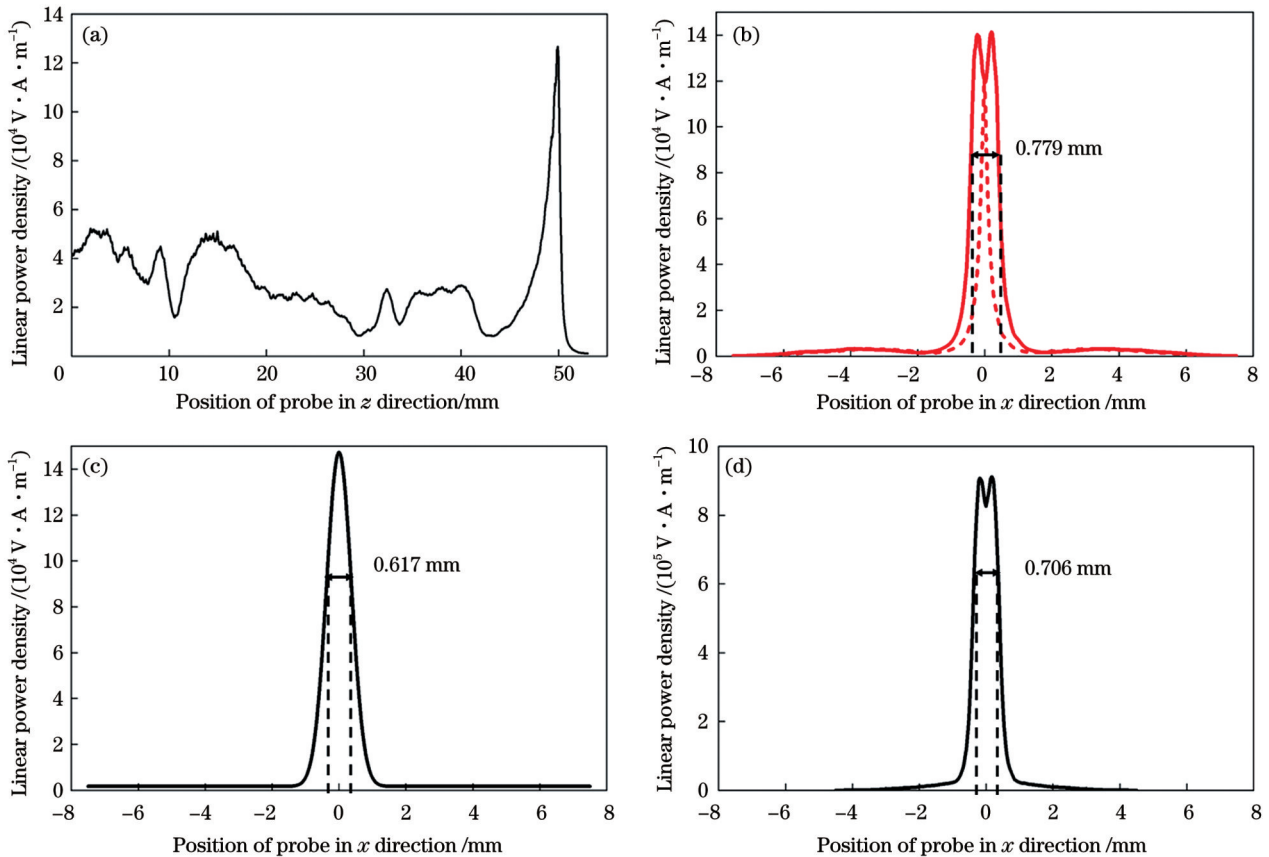


图 3 锥尖半径为 0.2 mm 的太赫兹探针的聚焦效果。(a)0.1 THz 处探针在  $z$  方向的功率线密度分布图;(b)0.1 THz 处探针在  $z=50$  mm 处  $x$  方向的功率线密度分布图;(c)根据图 3(b)中的双峰结构拟合出的单峰结构;(d)0.2 THz 处探针在  $z=50$  mm 处  $x$  方向的功率线密度分布图

Fig. 3 Focusing effects of terahertz probe with tip radius of 0.2 mm. (a) Linear power density distribution of probe in  $z$  direction at 0.1 THz; (b) linear power density distribution of probe in  $x$  direction at  $z=50$  mm at 0.1 THz; (c) single peak structure fitted based on bimodal structure in Fig. 3(b); (d) linear power density distribution of probe at  $z=50$  mm at 0.2 THz

同时为了实现更高精度的太赫兹聚焦,我们在原来设计模型的基础上进行等比例缩小,将探针的锥尖

孔半径设定为 1  $\mu$ m,仿真结果如图 4 所示,同样能在探针出射端口处得到聚焦光斑,这说明这种探针可实现



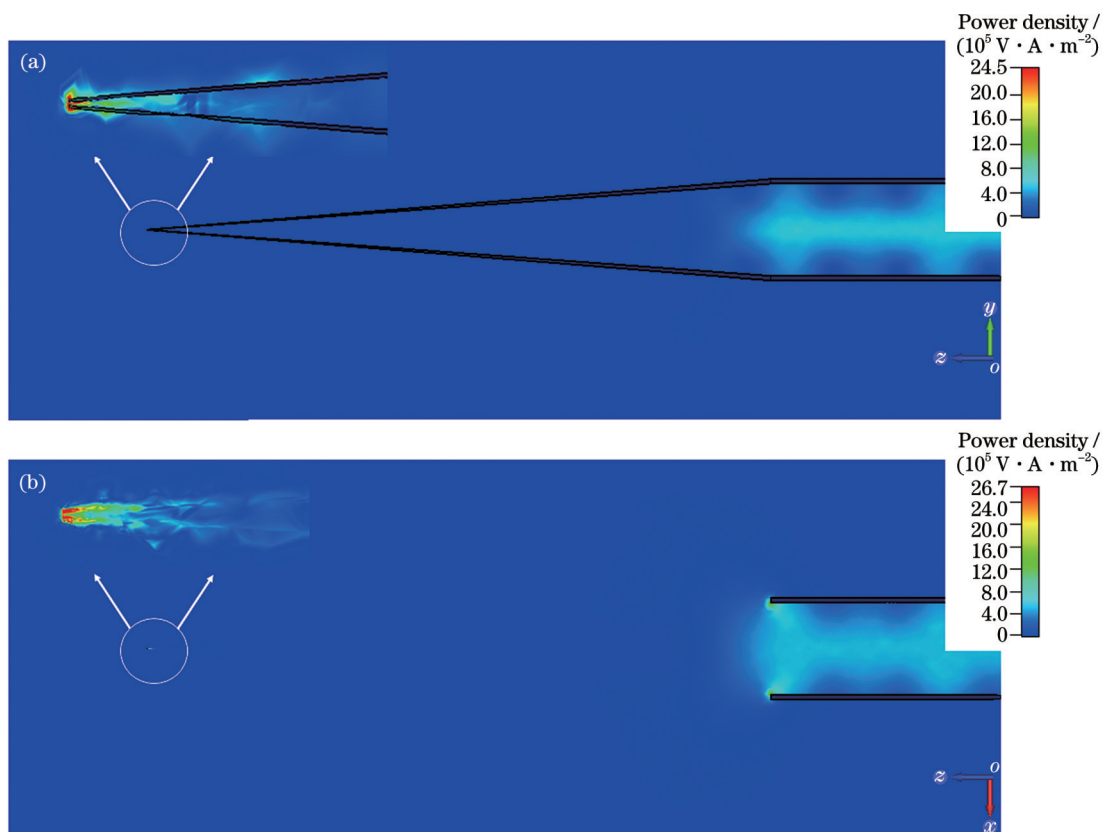


图 4 锥尖半径为  $1\ \mu\text{m}$  的太赫兹探针的能量密度分布示意图。(a)  $y$ - $z$  平面; (b)  $x$ - $z$  平面

Fig. 4 Power density distribution diagrams of terahertz probe with tip radius of  $1\ \mu\text{m}$ . (a) In  $y$ - $z$  plane; (b) in  $x$ - $z$  plane

更高的空间分辨率,无截止频率限制,从而证明了这种探针结构在更高分辨率下的可行性。但是,目前大多数精密加工工艺无法实现锥尖半径为  $1\ \mu\text{m}$  的金属薄壁针尖的精细加工,所以如果打印精度可以得到改善,那么太赫兹探针的空间分辨率也可以进一步提升,进而实现更精密的太赫兹超分辨成像。

### 3 探针制作以及太赫兹近场超分辨成像实验

根据仿真结果优化出渐变开口圆锥形探针的结构参数,之后进行太赫兹探针的加工制作。本文采用的是基于熔融沉积模型(FDM)的3D打印方法。该方法先用CAD软件建构出物体的数字3D模型图,然后将物体模型图输入到FDM打印的装置中,最后将各种热熔性的丝状材料(丙烯腈-丁二烯-苯乙烯共聚物和尼龙等)加热熔化、堆叠成形。我们采用的是Ultimaker 2+Connect打印机,根据打印机的特性,在打印薄壁针尖时必须降低精度,因此为了保证近场探针的打印质量,我们将探针半径扩大为  $0.4\ \text{mm}$ 。同时,我们进一步对  $0.4\ \text{mm}$  半径的探针进行了数值仿真,仿真结果如图5所示。可以看到,太赫兹光斑在  $x$  方向的聚焦宽度为  $1.186\ \text{mm}$ ,  $y$  方向是  $0.8\ \text{mm}$ ,依然能够实现亚波长聚焦(小于  $1/2$  波长),进而实现超分辨成像。并且对探针锥尖处的功率透射率进行了仿真计算,在工作频率  $0.1\ \text{THz}$  处,所得

透射率为  $3.16\%$ ,相较于其他探针结构<sup>[13,16]</sup>,功率损耗较小。

之后我们用Solidworks软件对优化好的探针进行三维建模,并使用开源切片软件Cura进行切片,将切片后的代码文件传输进打印机进行打印。我们采用打印喷嘴直径为  $0.25\ \text{mm}$  的打印机喷头,打印机的三维运动轴在  $x$ 、 $y$ 、 $z$  方向可以实现  $12.5$ 、 $12.5$ 、 $5.0\ \mu\text{m}$  的分辨率,使用可实现较高打印精度的打印材料聚乳酸(PLA),打印结束后对打印成品表面进行金属镀膜。

样品制作完成后,我们用图6所示的二维近场扫描成像系统对探针的成像能力进行实验验证。我们采用内径为  $8\ \text{mm}$  的金属空心圆波导将  $0.1\ \text{THz}$  的太赫兹波传输到探针进行聚焦,聚焦后的亚波长太赫兹光斑照射到3D打印的分辨率板上,携带成像信息的太赫兹透射波被内径为  $4\ \text{mm}$  的金属空心圆波导接收,并传输到热释电探测器中,最后在计算机上进行成像。我们所使用的太赫兹源是  $0.1\ \text{THz}$  的太赫兹源,输出功率约为  $80\ \text{mW}$ ,所用探测器是热释电太赫兹探测器,探测带宽为  $0.1\sim 30\ \text{THz}$ ,噪声等效功率(NEP)为  $1\ \text{nW}$ ,最大测量功率为  $25\ \mu\text{W}$ ,灵敏度为  $140\ \text{kV}\cdot\text{W}^{-1}$ 。在实验过程中,样品放置在距离探针锥尖  $0.5\ \text{mm}$  处,扫描区域为  $5\ \text{cm}\times 5\ \text{cm}$ ,三维精密平移台在横向和竖向分别进行步长为  $0.1\ \text{mm}$  和  $0.48\ \text{mm}$  的移动。

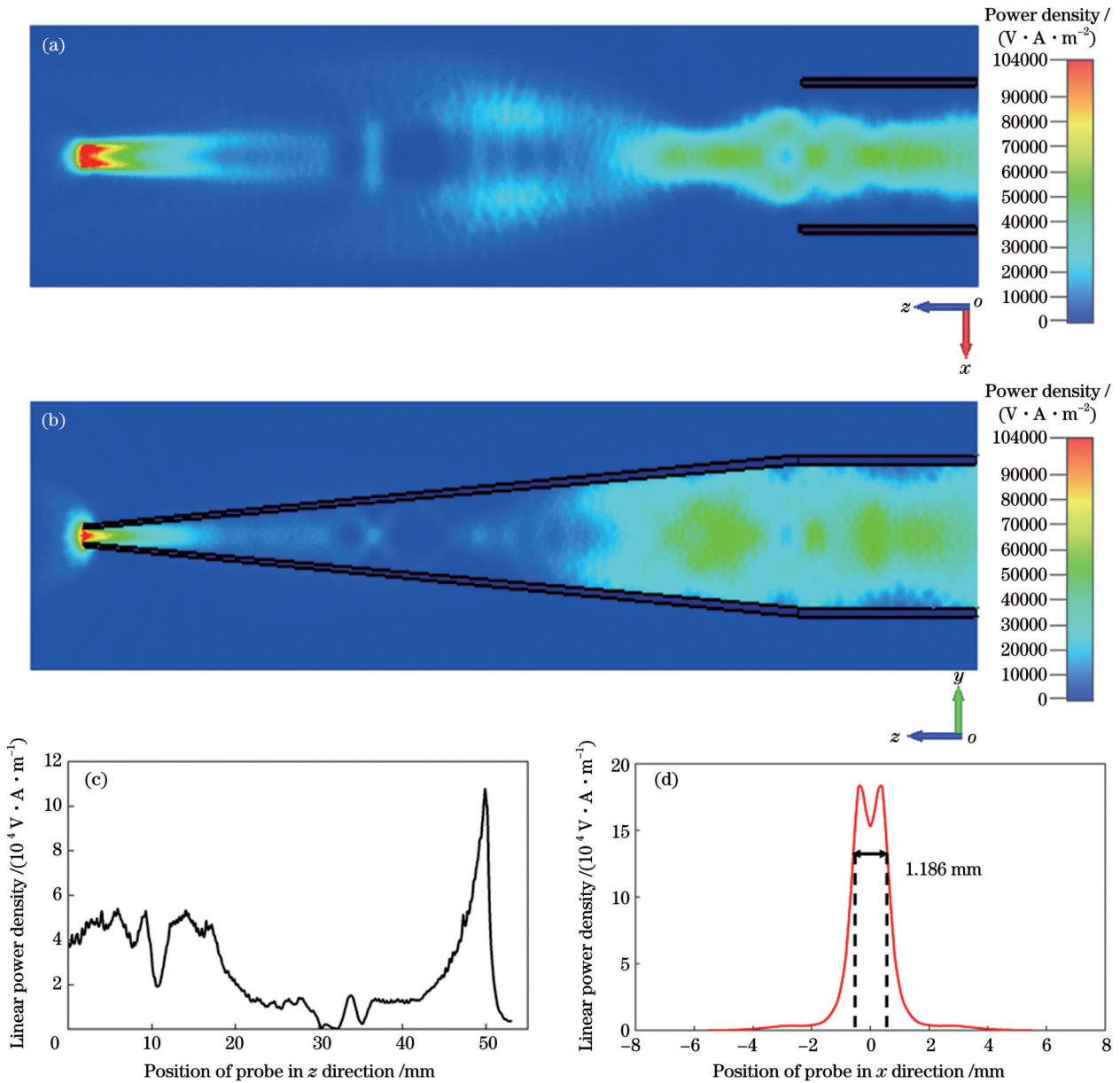


图5 锥尖半径为0.4 mm的太赫兹探针的仿真效果。(a)  $x$ - $z$ 平面的功率密度分布;(b)  $y$ - $z$ 平面的功率密度分布;(c)探针在 $z$ 方向的功率线密度分布图;(d)探针在 $z=50$  mm处 $x$ 方向的功率线密度分布

Fig. 5 Simulation results of terahertz probe with tip radius of 0.4 mm. (a) Power density distribution in  $x$ - $z$  plane; (b) power density distribution in  $y$ - $z$  plane; (c) linear power density distribution of probe in  $z$  direction; (d) linear power density distribution of probe in  $x$  direction at  $z=50$  mm

我们打印的分辨率板长为7 cm、宽为5 cm,对其进行扫描,成像结果如图7所示,宽度为2.0 mm和1.5 mm的缝隙都能完整呈现出来。并且我们也对线宽为2 mm的“nk”字样进行了成像,效果良好,实验结果与仿真结果一致。

## 4 结 论

提出了一种基于空心圆波导的渐变开口圆锥形近场探针设计方法。该探针继承了间隙探针的高信噪比、宽波段、无截止频率的优点,能够实现亚波长超分辨聚焦,理论上可实现微米级高分辨成像。为了验

证该方法的可行性,基于3D打印技术制备了针尖半径为0.4 mm的太赫兹近场探针结构,并搭建了一套太赫兹近场扫描成像系统进行成像实验。实验结果证明,该探针能够实现亚波长超分辨聚焦,在0.1 THz(波长为3 mm)下能够实现1.5 mm的成像分辨率,达到了1/2波长,实现了太赫兹超分辨成像。实验结果和仿真结果一致,证明了基于空心圆波导的渐变开口圆锥形近场探针的可行性。随着3D打印工艺的不断发展,基于空心圆波导的渐变开口圆锥形近场探针的针尖尺度将不断缩小,其分辨率还有广阔的提升空间。

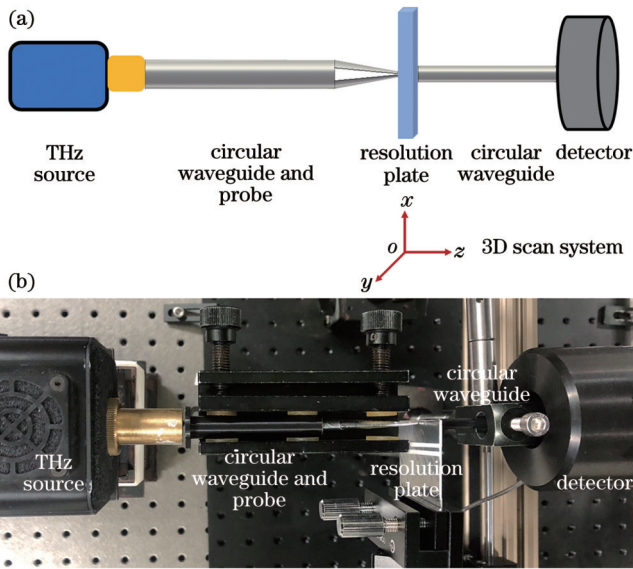


图 6 二维近场扫描成像系统。(a) 系统原理示意图; (b) 系统实物图

Fig. 6 Two dimensional near-field scanning imaging system. (a) Schematic of system principle; (b) physical drawing of system

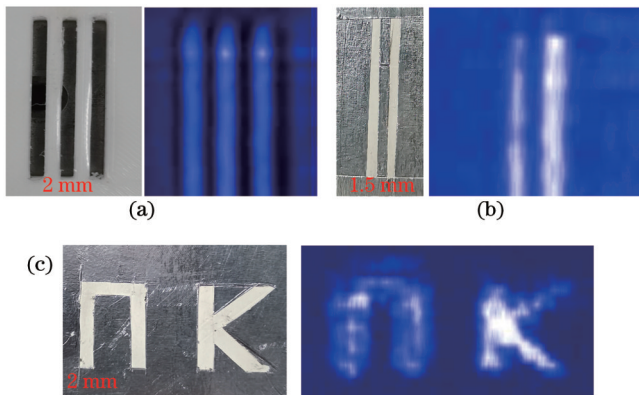


图 7 探针对分辨率板以及样品成像。(a) 宽度为 2.0 mm 的缝隙成像; (b) 宽度为 1.5 mm 的缝隙成像; (c) “nk” 字样样品成像

Fig. 7 Probe imaging of resolution plate and sample. (a) Slit imaging with width of 2.0 mm; (b) slit imaging with width of 1.5 mm; (c) imaging of “nk” sample

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# Terahertz Super-resolution Imaging Based on Open-Mouth Conical Near-Field Probe

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## Abstract

**Objective** Terahertz imaging technology has broad application prospects in several fields, such as biological detection, medical treatment, data communication, and non-destructive security. However, the long wavelength of terahertz wave, limited by diffraction limitations, only allows the resolution of traditional terahertz imaging technology to be of the wavelength order, which cannot accurately image material details such as biological cell tissues and chip internal circuits. Therefore, the development of terahertz super-resolution imaging technology is particularly important. However, the probes prepared based on traditional micro/nano processing technology present drawbacks such as complex processing and high transmission losses. Based on this, this study proposes a design method for a tapered opening near-field probe based on a hollow circular waveguide. This conical probe can surpass the cut-off wavelength limit to achieve sub-wavelength focusing. In addition, the designed probe is processed using 3D printing technology. Subsequently, a 0.1 THz near-field scanning imaging system is built based on a high-precision 3D scanning platform, and the imaging effect of the processed probe is experimentally tested. The experimental results show that the probe can achieve sub-wavelength super-resolution focusing and has high power transmittance, which verifies the feasibility of 3D-printed terahertz near-field probes.

**Methods** First, the structure and size parameters of the tapered probe with a gradient opening are designed. The probe structure is simulated and optimized using CST Studio2019 software. The power density distribution map is examined (Fig. 2). To accurately study the focusing effect of the tapered probe with gradient opening on terahertz waves, we numerically characterize the focused terahertz spot: plotting a linear power density distribution curve in the  $x$ -direction at the exit port of the probe tip, and considering the  $x$ -width at  $\sqrt{2}/2$  of the peak value as the focusing width of the terahertz spot (Fig. 3). After optimizing the optimal structural parameters of the probe through simulation, a digital 3D model diagram of the probe is exported. After slicing it in the software, the slicing file is input to a 3D printer for printing. After printing, the surface of the printed product is coated with metal. After the sample production is completed, we build a two-dimensional near-field scanning imaging system to experimentally verify the imaging ability of the prepared probe sample (Fig. 6) and evaluate its imaging resolution.

**Results and Discussions** The simulation results of the probe reveal that the designed probe structure bypasses the influence of the cut-off wavelength. The incident terahertz frequency is 0.1 THz, and terahertz focusing can be achieved when the probe tip radius is 0.2 mm. The  $x$ -direction focusing width is 0.779 mm, and the  $y$ -direction focusing width is 0.4 mm, according to the physical aperture size. In theory, the conical probe structure can achieve a close resolution of  $1/4$  wavelength, which is super-resolution imaging. Simultaneously, we simulate the focusing spot size of probes with the same size at 0.1 THz and 0.2 THz (Fig. 6). The linear power density of the focusing spot at 0.2 THz is roughly 6 times that of the focusing spot at 0.1 THz; the diameter of the focusing spot at 0.1 THz is approximately 0.779 mm; and the one at 0.2 THz is approximately 0.706 mm, with a difference of approximately 0.073 mm. The higher the frequency, the smaller the diameter of the focusing spot, and the higher the resolution. To demonstrate that this probe structure can achieve higher precision terahertz focusing, a proportional reduction is made on the basis of the original design model, and the cone tip aperture of the probe is set to  $1\ \mu\text{m}$ . This can also form a focused spot at the exit port of the probe. To ensure the printing quality of the near-field probe, we expand the tip radius of the probe to 0.4 mm, and the focusing width of the terahertz spot in the  $x$  direction is 1.186 mm, with an power transmittance of 3.16%. In experiments, the imaging resolution of the probe with a tip radius of 0.4 mm is 1.5 mm, and the imaging resolution reaches  $1/2$  wavelength. The experimental results are consistent with the simulation results.

**Conclusions** This study proposes a design method for a tapered opening near-field probe based on a hollow circular waveguide. Through simulation analysis, this probe inherits the advantages of a high signal-to-noise ratio, a wide band, and no cut-off frequency of gap probes and can achieve sub-wavelength super-resolution focusing. Theoretically, it can achieve micron-level high-resolution imaging. To verify the feasibility of this method, we prepare a terahertz near-field probe structure with a tip radius of 0.4 mm based on 3D printing technology and built a terahertz near-field scanning imaging system for experiments. The experimental results demonstrate that the probe can achieve sub-wavelength super-resolution focusing, achieving an imaging resolution of 1.5 mm at 0.1 THz, reaching  $1/2$  wavelength, and achieving terahertz super-resolution imaging. The experimental results are consistent with the simulation results, proving the feasibility of a tapered near-field probe based on a hollow circular waveguide.

**Key words** optical design; 3D printing; near-field probe; terahertz; super-resolution