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※封面论文※

基于人工局域表面等离激元的高灵敏传感研究进展（特邀）

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摘　要：人工局域表面等离激元是一种基于表面等离激元超材料的电磁谐振模式，在微波、毫米波和太赫兹频段可实现深亚波长场束缚、高品质因子、高介电灵敏度等优异传感特性，并且与平面印刷电路工艺兼容，易于和信号检测电路、无线通信电路集成，因此在小型化便携式的物联传感领域展现出广阔的应用前景。本文重点介绍人工局域表面等离激元传感的新原理、相关技术及典型应用。在传感新原理方面，讨论了新型人工局域表面等离激元的谐振结构、电磁模式、以及涡旋波传感原理；在传感指标提升技术方面，探讨了模式间耦合和有源放大两种传感增强方法；在应用探索方面，回顾了人工局域表面等离激元在溶液浓度传感、细胞传感和力学量传感等方向的代表性工作，介绍了小型化人工局域表面等离激元传感系统的最新进展。最后，对人工局域表面等离激元传感的发展趋势进行了讨论和展望。

关键词：电磁谐振；人工局域表面等离激元；传感增强；传感灵敏度；传感系统
中图分类号：O441　　**文献标识码**：A　　**doi**：10.3788/gzxb20235210.1052401

0 引言

人工局域表面等离激元（Spoof Localized Surface Plasmons, SLSPs）基于电磁超材料的人工微结构，在微波、毫米波等频段构造等效的负介电常数，从而重现光学频段局域表面等离激元的谐振模场分布、亚波长场局域性、对介电环境的高度敏感性等优异特性[1,2]。此概念在2012年由英国帝国理工学院的PENDRY John教授首次提出，并在二维无限深的金属刻槽结构中进行了理论和仿真分析[2]。2014年，东南大学的崔铁军院士团队通过理论和实验证明，超薄金属图形也可以支持人工局域表面等离激元谐振模式，从而将人工局域表面等离激元从物理概念推向了平面印刷电路应用[3,4]。之后，人工局域表面等离激元得到了国内外学者的广泛关注和跟踪研究，并在微带滤波器、小型化谐振天线等器件设计、微波和太赫兹高灵敏传感等领域中得到应用验证[1,5-9]。

人工局域表面等离激元作为一种新型的电磁谐振模式，有望解决传统微波谐振传感发展的瓶颈问题。微波谐振传感表现为谐振频率随周围介电环境的变化，具有实时无标记的传感能力和优异的环境适应性，基于不同的敏感材料（transducer materials）可以实现灵活多样的物理、化学和生物传感功能。但受限于波长，微波谐振传感无法达到光学谐振传感的单分子检测精度[10,11]，难以满足微量目标检测的实际需求。近年

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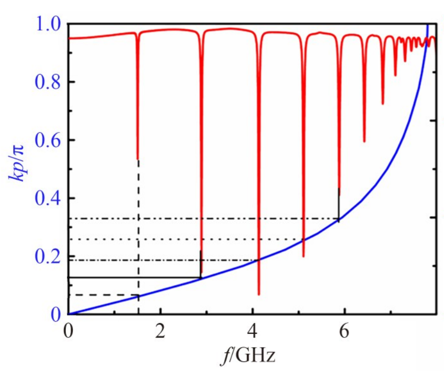
来的研究证实，人工局域表面等离激元的深亚波长场束缚性已经突破百分之一波长[12]，有望在鲁棒性高、造价经济的低频段，实现等效波长所对应的高灵敏度，从而突破微波谐振传感对微量目标的检测极限[13]。并且，得益于金属在微波等低频段的低欧姆损耗，以及人工微结构的设计灵活性，人工局域表面等离激元可以实现丰富的高阶谐振模式以及高品质因子[5, 12]。此外，人工局域表面等离激元可以和信号检测电路以及通信电路集成，从而发展出高度集成化小型化的传感系统，有望推动万物互联时代下传感技术的发展升级[1]。

1　人工局域表面等离激元传感的新探索

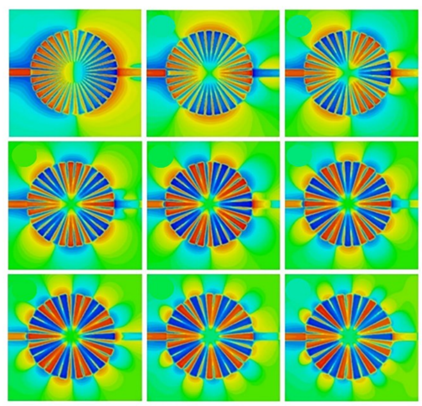
人工局域表面等离激元是2012年提出的新概念，其在印刷电路中的典型结构和谐振模式如图1所示。得益于人工微结构丰富灵活的设计和调控特性，大量的新原理、新现象持续涌现。准连续体中束缚态（Quasi-bound states in the continuum，Quasi-BICs）、斯格明子（skyrmions）、奇异点（Exceptional Point，EP）、涡旋波（vortex mode）等新型人工局域表面等离激元电磁模式，带来了传感指标的持续提升和新颖的传感功能。扇形结构、折纸超材料等新型谐振结构的出现，为人工局域表面等离激元传感带来了全新的发展空间。同时，太赫兹频段的人工局域表面等离激元传感技术也经历了一定的发展，并展现了可观的应用价值。

(a) Photograph of the printed spoke-pattern SLSP[3]

(b) Photograph of the printed spiral SLSP[4]



(c) Typical spetra of SLSPs with multimode and high-Q resonances [12]



(d) Field distributions of multiple electric resonances in SLSP[5]

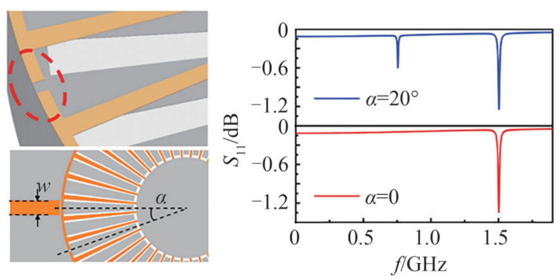
图1　人工局域表面等离激元典型的结构和模式性质[3-5, 12]

Fig. 1　Typical spoof localized surface plasmons′ structures and modal properties[3-5, 12]

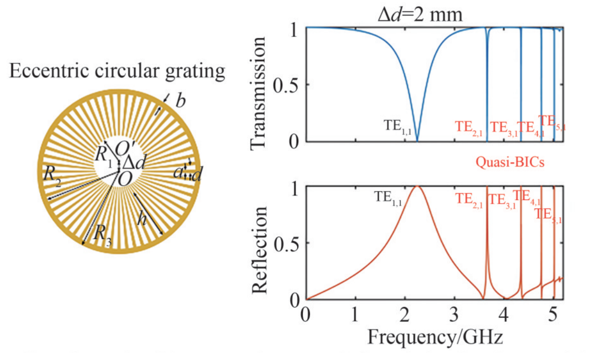
1.1　人工局域表面等离激元的新型电磁模式

连续体中的束缚态是一类不具有辐射的电磁本征态，不能被直接激发。研究发现通过调整系统构型、周期边界等可以获得连续体中束缚态的辐射泄漏模式，即连续体中的准束缚态，表现为在亚波长尺度形成高密度、局域化的电磁场能量增强，具有高品质因子的特性。近几年，人工局域表面等离激元单元及阵列结构中的准连续体中束缚态效应被陆续报道，实现了品质因子的持续提升[12, 14, 15]。2021年东南大学崔铁军和张璇如团队[12]基于微带电路激励的人工局域表面等离激元谐振器，通过引入狭缝破坏结构的对称性，极大抑制了辐射损耗，实现了电偶极子和磁偶极子的混合模式，将谐振器直径压缩至1/20波长以内，并实验测得

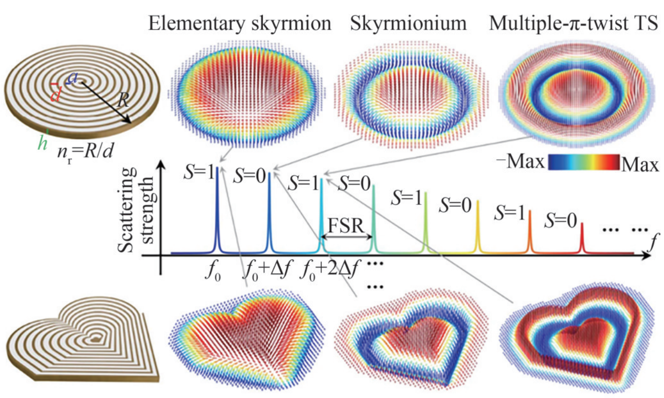
了53.3的品质因子，如图2(a)。2022年北京大学的杜朝海团队[15]在空间波激励的人工局域表面等离激元阵列结构中，采用偏心方式打破结构的旋转对称性，同样抑制了结构的辐射损耗，实现了准连续体中束缚态效应，实测品质因子高达214.8，如图2(b)所示。



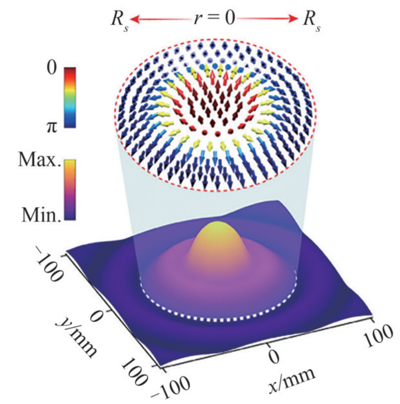
(a) Schematic of the slit which breaks the symmetry, and the reflectance spectra of the dipole modes in[12]



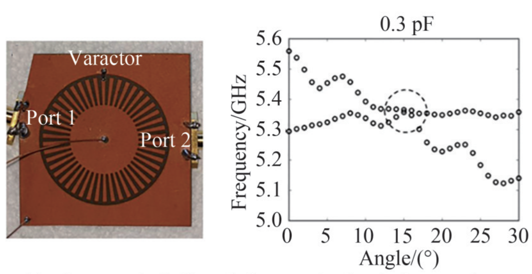
(b) Schcmatic of the eccentric SLSP (left) and simulated transmision and reflection of the eccentric SLSP array (right)[15]



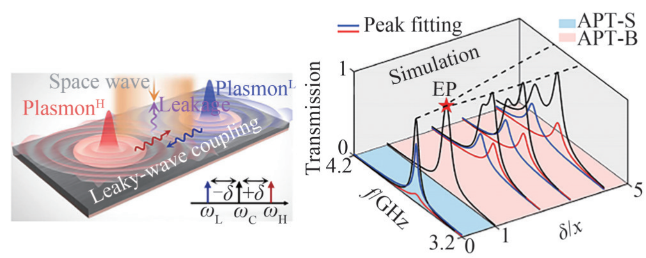
(c) The plasmonic shyrmion structures made of a single-armed metallic spiral stripe (left), their scattering spectra and the vectorial magnetic field configurations of their resonance modes (right)[18]



(d) Illustration of the SLSP skyrmion[19]



(e) Photograph (left) and eigenmode simulation result (right) of the actively tunable EP phenomenon[25]



(f) Using spatial waves to construct EP phenomenon (left) and its near-field-measured transmission spectra (right)[26]

图2　人工局域表面等离激元的新型电磁模式[12, 15, 18, 19, 25, 26]

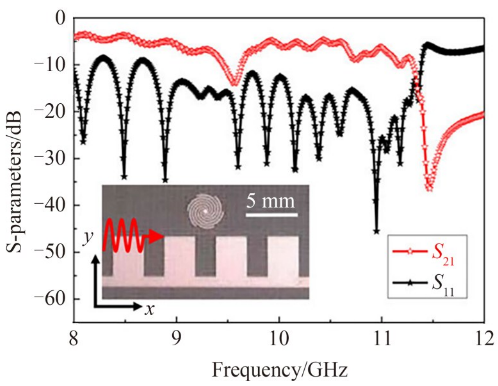
Fig. 2　Novel electromagnetic modes of spoof localized surface plasmons[12, 15, 18, 19, 25, 26]

斯格明子由于其特殊的拓扑不变性而引起了广泛的关注，为矢量场拓扑特性的分析和控制提供了新的方法[16, 17]。2021年暨南大学的邓子岚和李向平团队[18]基于单螺旋人工局域表面等离激元谐振结构实现了磁质斯格明子并证明了该斯格明子的拓扑不变性，如图2(c)所示。该结构还实现了与空间形状无关的谐振特性和深亚波长谐振模式，为基于人工局域表面等离激元的高灵敏度、柔性传感应用提供了新思路。2022年比利时鲁汶大学的郑学智、杨杰和空军工程大学的王甲富等[19]证明了一个具有旋转和镜像对称性的人工局域表面等离激元谐振器的电场矢量呈现斯格明子模式，如图2(d)所示；该团队也提出了应用群表征理论分析斯格明子对称性起源的新方法[20]，证明了斯格明子在任何具有旋转和镜像对称性的平面电磁谐振器中普

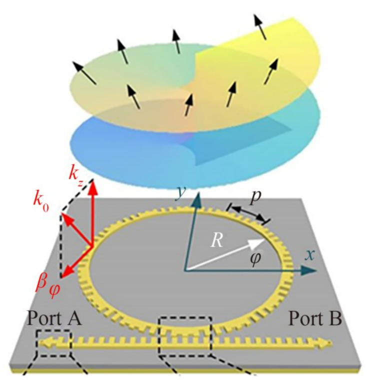
遍存在。

除谐振频移检测之外，谐振传感还存在另外一种重要的形式，即对微扰散射体引起的谐振峰劈裂信号的传感。应用非厄米系统中的特殊模态简并现象——奇异点，可以使得共振频移或分裂与扰动强度呈平方根依赖性，极大增强了谐振峰劈裂传感对极微小扰动信号检测的灵敏度。奇异点现象最初用于增强光学微腔对微小散射体的检测信号[21-24]，近两年才发展到微波段的人工局域表面等离激元领域。2023年韩国国立蔚山科学技术院JUN Y C等[25]通过变容二极管的容值调节人工局域表面等离激元谐振模态间的耦合作用，实现了对奇异点的主动调控，如图2(e)。此工作为奇异点在集成器件和可调元件中的应用提供了有效方案。2022年浙江大学陈红胜和高飞团队[26]发现在两个人工局域表面等离激元谐振器组成的二聚体结构中，通过操控入射空间波的极化状态调节入射空间波与谐振器平面外辐射波之间的耦合，可以实现极化控制的奇异点现象，如图2(f)。此工作首次阐明了利用空间波构建奇异点的物理机理和实现方法，可以为基于奇异点的空间无线传感提供思路。

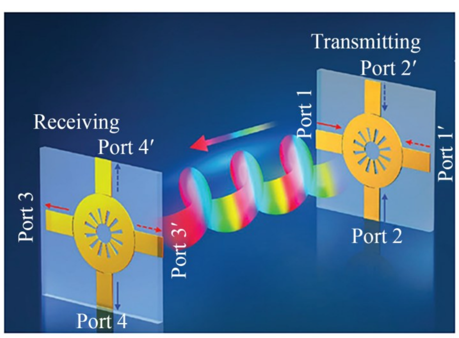
涡旋波表现为电磁场涡旋状的相位波前，此概念经常与轨道角动量(Orbital Angular Momentum，OAM)联系在一起，可以为电磁波提供频率、幅度、相位、极化之外的又一信息维度，在超高速超大容量通信、涡旋波雷达等领域展示了丰富的应用潜力[27-31]。常见涡旋波产生技术都依赖于螺旋相位板、阵列天线、超表面等提供相位梯度的阵列结构[32-36]，而单个人工局域表面等离激元谐振单元也可产生多阶涡旋波模态，展示出更紧凑的结构尺寸、更灵活可调谐性、和更丰富的应用场景[37-40]。2018年南京大学的王振林团队[37]利用人工表面等离激元(Spoof Surface Plasmons，SSPs)波导的传输模式，选择性激发人工局域表面等离激元中的涡旋波模式，如图3(a)所示。对不同尺寸的人工局域表面等离激元，可以产生具有不同拓扑电荷的涡旋波模式。2020年杭州电子科技大学的罗国清和廖臻团队[38]采用周期性结构调制的人工表面等离激元环形谐振器，实现了涡旋波的高效辐射，在不同频率下产生了多阶的涡旋波模式，如图3(b)。后续工作中，该



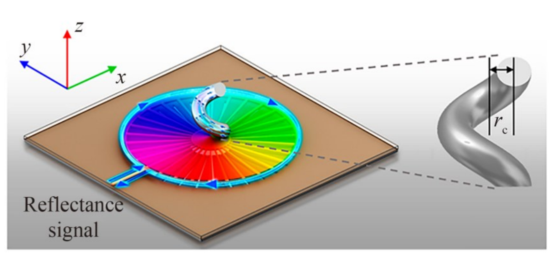
(a) Measured S-parameters of the hybrid waveguide combined with meta-particle[37]



(b) SSP ring resonator that emits multiplexed vortex waves[38]



(c) Vortex mode transceiving using SLSPs[40]



(d) Single-particle dichroism using vortex modes in a SLSP[44]

图3 基于人工局域表面等离激元的微波涡旋波研究[37,38,40,44]

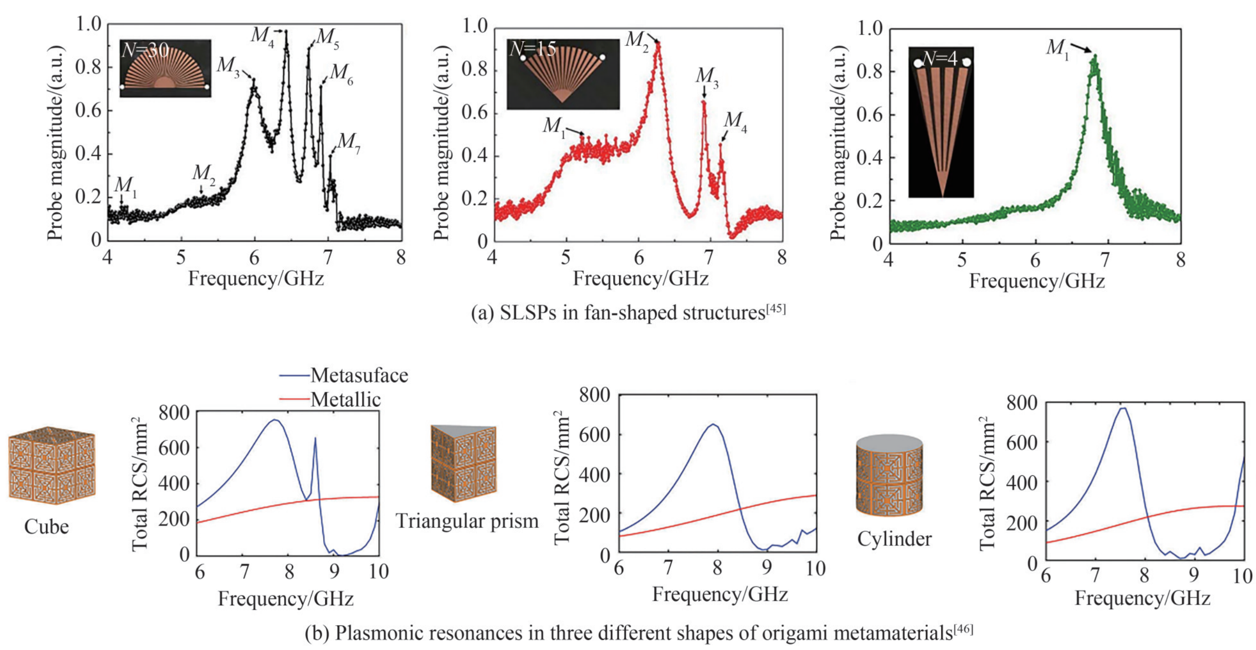
Fig. 3 Microwave vortex wave studies based on spoof localized surface plasmons[37,38,40,44]

团队在结构中引入变容二极管,实现了对涡旋光束的动态可重构[39]。2022年东南大学崔铁军和张璇如团队[40]提出了一种基于正交简并辐射模式间叠加分解的微波涡旋波收发方案,如图3(c)所示。该方案采用相同的人工局域表面等离激元谐振器作为发射天线和接收天线,通过改变发射天线激励端口处的相位,即可对涡旋波模态进行连续调控;接收到的涡旋波模态可由接收端口处的幅度和相位信号方便地表征。相对于传统的天线阵列或扫描探针进行空间相位梯度测量,这项工作为涡旋波的接收和探测提供了更加紧凑便捷的方案。

涡旋波的螺旋相位波前可以提供丰富的信息维度,有望提升其对散射体形状、方位角、旋转速度等物理量的探测能力[41-44]。2020年东南大学的崔铁军和张璇如团队[44]在人工局域表面等离激元结构中激励了束缚态的涡旋波模态,将一阶涡旋波模态压缩至1/11波长直径以内,并利用其高品质因子的谐振峰,实现了对直径1/60波长手性颗粒的实验探测,如图3(d)。这项工作揭示了人工局域表面等离激元涡旋波传感在手性分子检测领域的应用潜力。

1.2 人工局域表面等离激元的新型谐振结构

随着人工局域表面等离激元的蓬勃发展,扇形结构、折纸超材料等新型谐振结构的出现,为人工局域表面等离激元传感器设计提供了新思路和新方法。2016年新加坡南洋理工大学的张柏乐和南方科技大学的高振等[45]研究了扇形的人工局域表面等离激元结构,如图4(a)。常见的圆形人工局域表面等离激元结构中的电谐振,可以理解为传播的人工表面等离激元围绕圆周长形成的驻波[5],而扇形人工局域表面等离激元是基于电磁波在扇形边界处的来回反射,形成类似Fabry-Perot共振效应。这样,通过改变光栅数就可以实现谐振频率和谐振模式的调谐,为设计人工局域表面等离激元谐振器提供了一种便捷的新方法。



(a) SLSPs in fan-shaped structures[45]

(b) Plasmonic resonances in three different shapes of origami metamaterials[46]

图4 人工局域表面等离激元的新型谐振结构[45,46]

Fig. 4 Novel resonance structures of spoof localized surface plasmons[45,46]

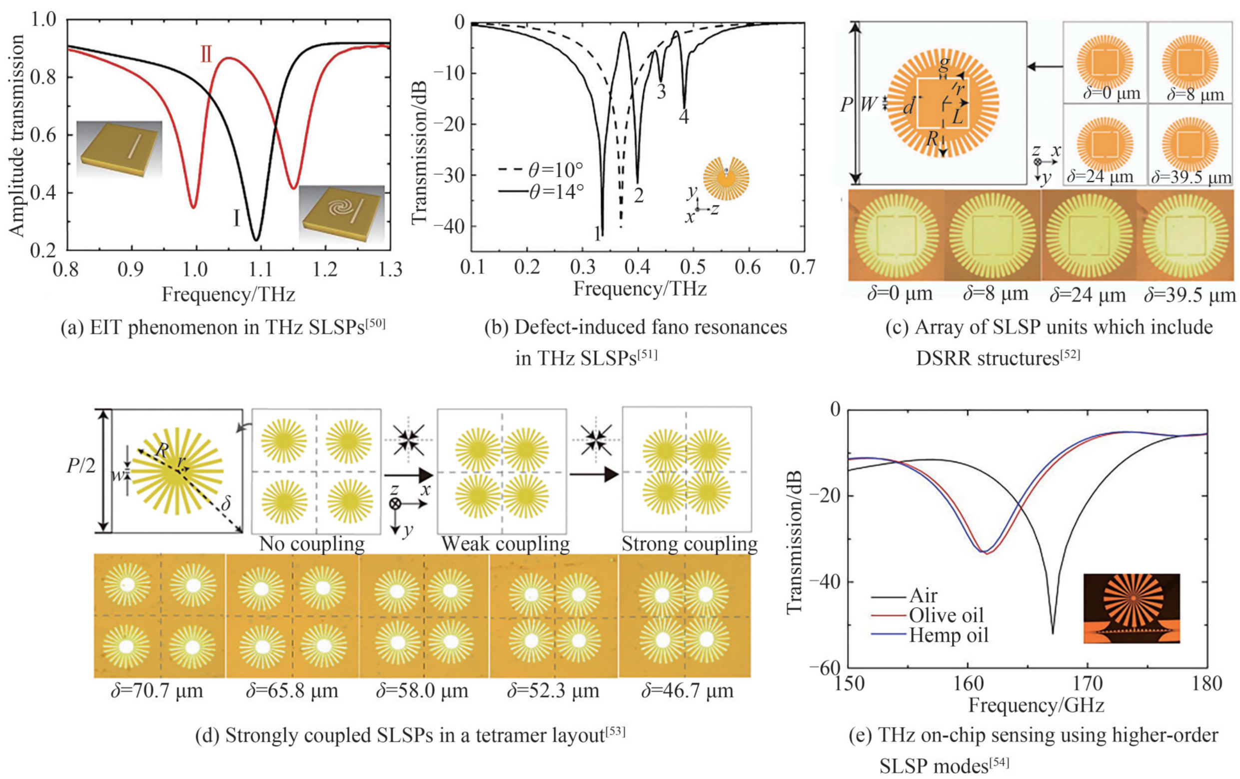
2023年浙江大学陈红胜和王作佳团队[46]报道了一种折纸超材料结构中的一阶杂化等离激元共振,该结构由相互连接的网格型超表面作为超薄金属薄膜进行折叠得到,可构建正方形、三棱柱形、圆柱形等三维结构,这些结构都支持三维的人工局域表面等离激元共振,如图4(b)。这种新颖的三维折纸超材料结构为人工局域表面等离激元带来了更广阔的思路和可能。

1.3 太赫兹人工局域表面等离激元传感

太赫兹(terahertz)频段位于微波毫米波与红外可见光之间,连接了电子学和光子学领域,具有独特的性质。由于大量有机分子的振动转动能级都落在太赫兹频段,表现为太赫兹特征吸收峰,因此,太赫兹传感受

到了极为广泛的关注。人工局域表面等离激元可以在太赫兹频段产生[47-49]，然而，受限于加工精度、材料属性、以及太赫兹产生探测技术，太赫兹人工局域表面等离激元难以实现微波频段那样灵活多变的设计，品质因子等指标的提升也面临更大的挑战。

2016年东南大学崔铁军、廖臻等[50]用螺旋形人工局域表面等离激元谐振器与短截线间耦合，在太赫兹频率下实现电磁诱导的透明效应（Electromagnetically Induced Transparency, EIT），如图5(a)所示。2017年上海理工大学朱亦鸣等[51]在人工局域表面等离激元上引入扇形缺角来打破空间对称性，构建了更加尖锐的法诺（Fano）共振峰，仿真测得的最佳的性能指数（Figure of Merit，FoM）达到16.4，品质因子达到32.6，如图5(b)所示。2023年苏州纳米技术与纳米仿生研究所的秦华和上海师范大学的赵振宇等[52]在人工局域表面等离激元内部引入双间隙开口环谐振器（Double-gap Split-Ring Resonator, DSRR）来构造模式间干涉，形成等离激元诱导透明（Plasmon-Induced Transparency, PIT）窗口，如图5(c)所示。随着系统的不对称性增加，可激励多个透明窗口，且形成Quasi-BICs模式，实测品质因子最高可达23.2。同年，秦华、赵振宇等[53]提出了一种强耦合四聚体结构的人工局域表面等离激元阵列，通过电磁仿真和加工测试，证实此结构下人工局域表面等离激元的相互作用引起了边缘模式（edge modes），边缘模式较同频率下本征模式有较高品质因子，实测品质因子最高可达15.8，如图5(d)所示。



(a) EIT phenomenon in THz SLSPs[50]
(b) Defect-induced fano resonances in THz SLSPs[51]
(c) Array of SLSP units which include DSRR structures[52]
(d) Strongly coupled SLSPs in a tetramer layout[53]
(e) THz on-chip sensing using higher-order SLSP modes[54]

图5 太赫兹频段的人工局域表面等离激元[50-54]

Fig. 5 Spoof localized surface plasmons in terahertz frequency[50-54]

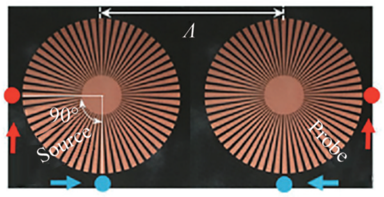
上述太赫兹人工局域表面等离激元的研究都是基于太赫兹时域光谱技术（Terahertz Time-Domain Spectroscopy, THz-TDS）对空间波激励下的阵列结构进行测量，适用于较高太赫兹频段的宽频响应研究。为实现更高的集成度，半导体集成电路成为太赫兹技术发展的趋势。2020上海理工大学朱亦鸣团队[54]通过人工表面等离激元波导激发人工局域表面等离激元高阶径向模式，如图5(e)所示，实现了对不同食用油的区分传感。2021年印度理工学院PATHAK N P团队[55]设计了太赫兹人工局域表面等离激元传感器，采用人工表面等离激元传输线端耦合激励，仿真品质因子达到192，有望为发展片上生物传感系统开拓道路。

2　人工局域表面等离激元的传感增强技术

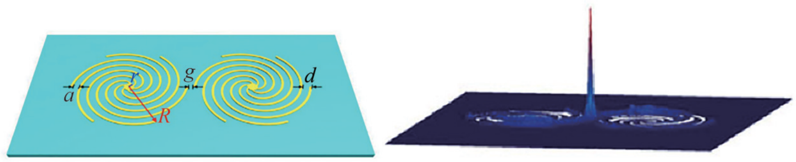
电磁谐振传感技术的核心指标包括传感灵敏度、品质因子和激励效率。传感灵敏度决定了相同检测目标下谐振峰频移量的大小，而品质因子和激励效率决定了谐振峰频移量的检测难度。对于人工局域表面等离激元传感，在谐振器结构和电磁模式设计之外，可以通过模式耦合构造电磁能量高速汇聚的传感热点结构，或构造高灵敏的杂化模式，进而提升传感灵敏度。加载有源放大器来补偿传感结构中的损耗，也可以实现品质因子和激励效率的提升。

2.1　人工局域表面等离激元的耦合增强原理

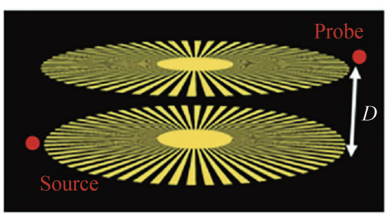
多层印刷电路板结构为人工局域表面等离激元的耦合增强研究提供了丰富的可能：在人工局域表面等离激元结构之间，可以灵活地构造平面内耦合、层间耦合，在单个人工局域表面等离激元结构内部，也可以构造不同模式间的耦合，如图6所示。



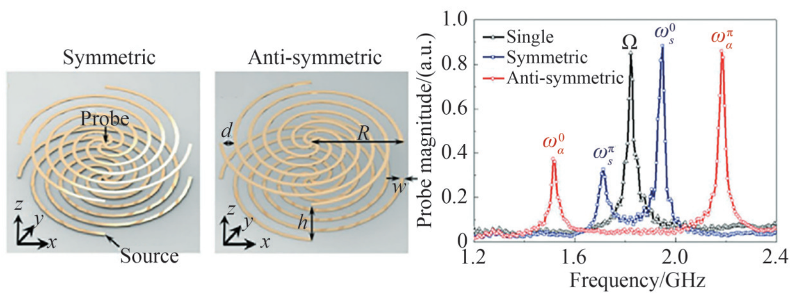
(a) Horizontal coupling between two SLSPs[56]



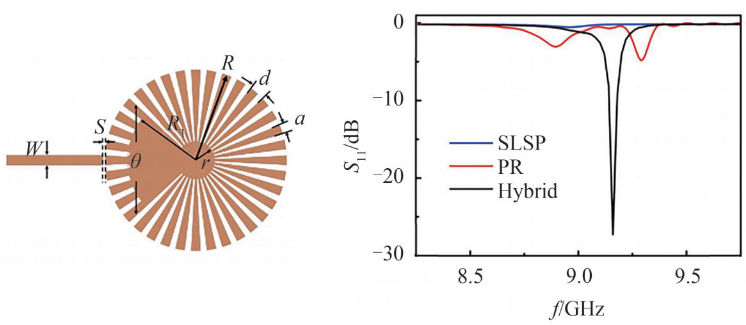
(b) Horizontal coupling between two spiral SLSPs (left) and its field enhancement effect (right)[57]



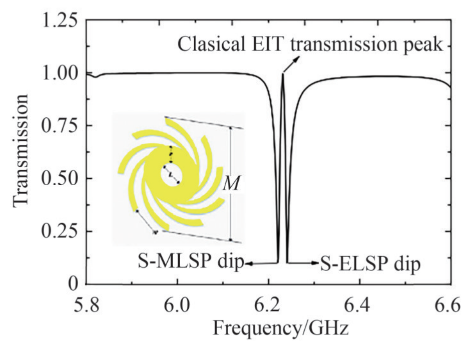
(c) Vertical coupling between two SLSPs[58]



(d) Vertical coupling between two spiral SLSPs that are stacked symmetrically and antisymmetrically (left) and their resonance spectra (right)[59]



(e) Geometry (left) and simulated reflectance (S_{11}) of the SLSP, PR, and the hybrid plasmonic resonator (right)[60]



(f) High-Q EIT resonance in SLSPs[61]

图6　基于模式耦合的人工局域表面等离激元谐振增强[56-61]

Fig. 6　SLSP resonance enhancements based on mode coupling[56-61]

图6(a)展示的是新加坡南洋理工大学张柏乐和南方科技大学高振等[56]对人工局域表面等离激元电谐振模式的平面内耦合的研究工作，研究发现：在谐振器圆周场强度分布的极大处或极小处耦合，其耦合因子大小相等、符号相反，此项工作为人工局域表面等离激元结构间耦合因子的调节提供了有效思路。图6(b)展示的是东南大学崔铁军和张婧婧团队[57]对人工局域表面等离激元磁谐振模式的平面内耦合的研究工作，利用紧密排列的两个螺旋形人工局域表面等离激元间的模式杂化，实现对电磁能量的高度汇聚，对局域电

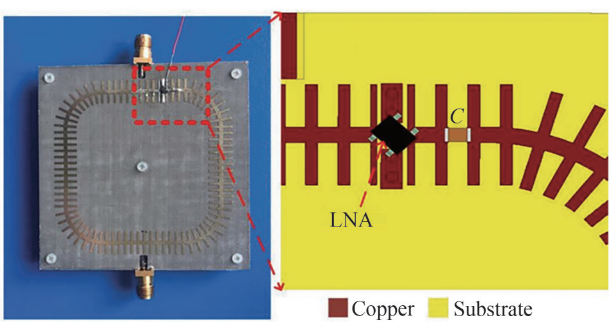
场＞5 000倍的增强，形成局域的传感热点结构。

围绕人工局域表面等离激元的层间耦合形式，2016年新加坡南洋理工大学张柏乐与浙江大学高飞等[58]通过垂直堆叠的两个人工局域表面等离激元之间的强耦合，观察到一个具有不对称法诺线形的谐振谱，如图6(c)所示。同年，新加坡南洋理工大学张柏乐、南方科技大学高振等[59]将两个螺旋形人工局域表面等离激元竖直方向堆叠杂化构成二聚体，包括对称堆叠和反对称堆叠两种形式，如图6(d)所示。理论和实验研究揭示，这样的两个人工局域表面等离激元磁谐振之间，磁耦合机制处于主导地位。

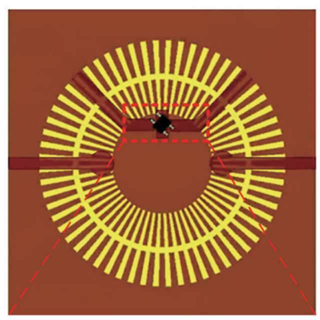
考虑传感应用需求，需要将人工局域表面等离激元在微带电路中激励，并在单个人工局域表面等离激元单元内部构造耦合效应，以减小器件尺寸。2020年东南大学崔铁军、张璇如[60]将一个扇形的扰动谐振(Perturbing Resonator, PR)结构与人工局域表面等离激元谐振器叠放，形成混合模式的人工局域表面等离激元谐振器，如图6(e)所示。基于扇形扰动结构的两个电谐振模式与原人工局域表面等离激元的磁谐振模式间的干涉，该混合模式谐振器形成了一个尖锐的谐振峰，相比于原人工局域表面等离激元谐振器，品质因子增强了3.4倍，FoM增强了79.8倍，灵敏度增强了4.1倍，传感FoM增强了12.8倍，实现了各传感指标的全面增强。2021年东南大学赵洪新等[61]提出一种对数螺旋结构的阵列单元，在一个螺旋形人工局域表面等离激元内嵌同心金属圆环，电共振和磁共振同时被一个连接的金属基本单元激发，仿真实现了品质因子高达311的谐振透明窗口，如图6(f)所示。

2.2 人工局域表面等离激元的放大增强技术

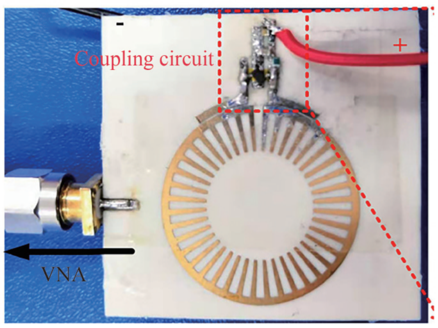
为提升谐振的品质因子，除无源结构优化和耦合效应之外，最常用的方式是引入有源增益补偿损耗；对于微波谐振器而言，可以方便地利用集总的放大器芯片实现[62, 63]。人工局域表面等离激元具有灵活多变的结构设计可能，可以将低噪声放大器芯片加载在单元内部。2018年上海大学周永金等[64]率先提出了利用放大器芯片提升人工局域表面等离激元品质因子的方案。2019年东南大学崔铁军和上海大学周永金等[65]提出了一种方形双层结构的人工局域表面等离激元谐振器，利用层间杂化的作用产生法诺共振，再将放大器芯片加载到人工局域表面等离激元结构中，实现了对法诺共振模式的放大增强，如图7(a)所示。相比于无源结构下的法诺谐振，放大增强的品质因子从49提高到2 802，谐振强度从19.89提高到37.42 dB。



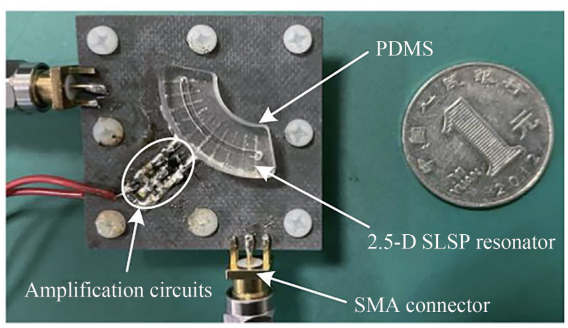
(a) Gain-assisted fano resonance in a double-layer SLSP[65]



(b) Schematic diagram of the active spoof plasmonic MIM ring resonator[66]



(c) Coupling circuit in gain-assisted half-integer SLSP mode[67]



(d) Amplification circuit for a quarter-mode 2.5D SLSP[68]

图7 人工局域表面等离激元的有源放大增强[65-68]

Fig. 7 Active amplification enhancement of spoof localized surface plasmons[65-68]

放大增强的另一种结构是在谐振器外侧引入耦合电路,将有源放大芯片置于耦合电路中。2019年上海大学周永金团队[66]设计了一种 金属-绝缘体-金属(Metal-Insulator-Metal,MIM)环形人工局域表面等离激元谐振器。通过在背部引入耦合枝节,使得只有四极模式被放大芯片选择性放大,通过调整偏置电压,测量的传输强度从−6.46 dB增加到10.74 dB,如图7(b)所示。2020年南京航空航天大学李茁、上海大学周永金等[67]通过在人工局域表面等离激元谐振器的狭缝附近引入主动耦合电路产生半整数阶模式,并采用有源放大技术显著提高品质因子,如图7(c)所示。在施加最佳偏置电压时,有源SLSP谐振器的半整数阶模式的测量品质因子从148增加到40 000。2022年杭州电子科技大学高海军、赵文生等[68]提出了一种基于四分之一模的2.5维人工局域表面等离激元传感器,如图7(d)所示。此结构采用双层结构实现耦合增强,提高传感器分辨率的同时,进一步减小谐振器尺寸,增强模场束缚性。在该结构中加载放大器,实测品质因子从无源情况下的56提升到4 247。

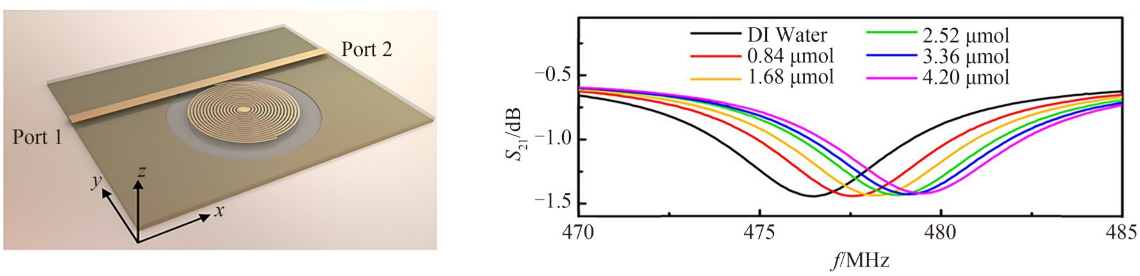
3 人工局域表面等离激元传感的应用研究

人工局域表面等离激元传感与其他电磁谐振传感技术一样,采用不同的敏感材料,可灵活应用于多种物理和化学传感器:如基于介电常数随溶液浓度或成分变化的生化传感器[69-73],以特异性吸附聚合物为敏感材料层的气体传感器[74-77]、基于柔性介质基板的力学量传感器[78-83]等。人工局域表面等离激元作为2012年提出的新概念,其应用研究尚处于探索阶段,本节将具体介绍部分代表性工作。

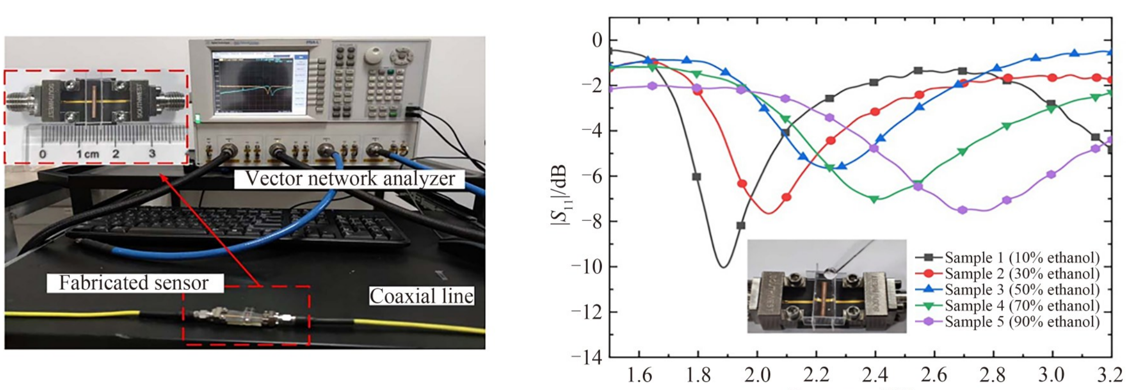
3.1 基于人工局域表面等离激元的溶液浓度传感

基于人工局域表面等离激元的溶液浓度传感已被报道应用于葡萄糖溶液、酒精溶液、油水混合物的检测,通常采用微流体通道来控制待测溶液形成一个相对稳定的传感环境[13, 67]。水溶液在微波频段的高介电常数和高介电损耗特性[84],对微波谐振传感的品质因子和谐振强度都提出了更高的要求。随着研究的推进,人工局域表面等离激元溶液浓度传感也从最初的传感功能演示,进入对检测极限指标的持续提升阶段。

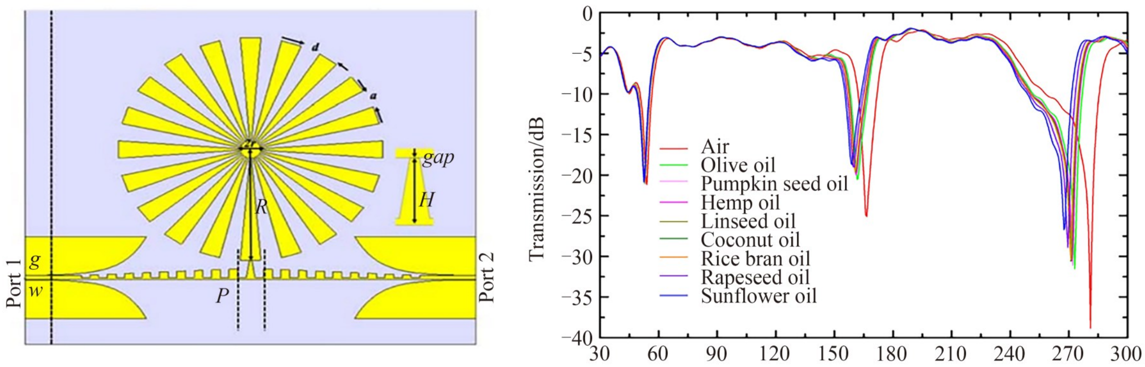
2022年东南大学的崔铁军和张璇如课题组[13]提出了一种深亚波长的人工局域表面等离激元谐振结构,将基模谐振压缩至1/41波长,测量品质因子达到187,如图8(a)。基于深度波长压缩,该结构在非接触传感



(a) Schematic of deep-subwavelength SLSP (left) and its performance in glucose sensing (right)[13]



(b) Photographs of the proposed effective localized surface plasmonic sensor (left) and its performance in ethanol concentration sensing (right)[70]



(c) Schematic of the THz SLSP sensing chip (left) and the transmission spectra of the SLSP in diferent edible oils[54] concentration sensing (right)[70]

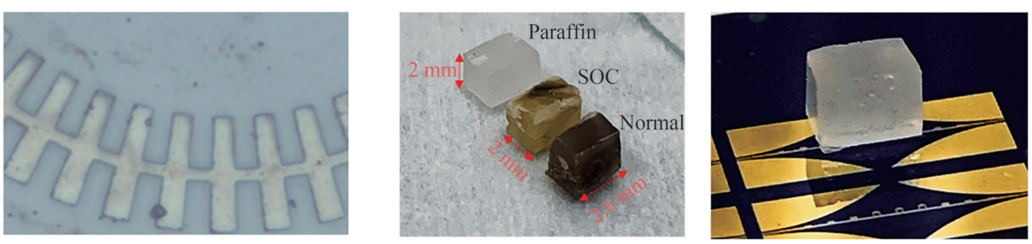
图8　基于人工局域表面等离激元的溶液浓度传感[13,54,70]

Fig. 8　Solution concentration sensing based on spoof localized surface plasmons[13,54,70]

方式下，利用0.63 m的工作波长实现了对15 μL溶液中0.45 μmol葡萄糖的检测。2021年南京航空航天大学的李茁课题组[70]提出一种三维结构的等效局域表面等离激元谐振器，具有0.008波长平方的超小型尺寸；利用该谐振器进行酒精溶液浓度传感，实现了高达0.57%的归一化灵敏度，如图8(b)，与类似技术相比具有明显的优势。2020年上海理工大学朱亦鸣等[54]利用片上集成的太赫兹人工局域表面等离激元，激励起高阶人工局域表面等离激元模式，证明高阶模式对介电环境变化具有更高的敏感性。并对不同的食用油（具有不同介电常数）进行了检测，如图8(c)。实验结果表明，三阶模式的灵敏度（45.64 GHz/RIU）接近基模灵敏度（5.07 GHz/RIU）的9倍，二阶模式的灵敏度（25.35 GHz/RIU）达到基模的5倍。

3.2　基于人工局域表面等离激元的细胞传感

相比于溶液浓度传感，单细胞传感需要更高的检测精度[85,86]。近年来，随着微波谐振传感灵敏度和检测极限等指标日益提升，基于微波谐振的细胞传感工作也在逐步展开[87,88]。2021年德国杜伊斯堡-埃森大学团队[89,90]制备了太赫兹频段的人工局域表面等离激元谐振结构，并实现从太赫兹天线到波导的高效耦合。该团队展示了此人工局域表面等离激元谐振器在细菌计数中的应用潜力，如图9(a)所示。对于其中最高品质因子的谐振模式，单个细菌的平均阻尼达到0.45 dB。2022年山东大学苏绚涛、张翼飞团队[87]提出一种带有开口谐振环的微波人工表面等离激元传感器，人工表面等离激元与开口环的相互作用实现了250倍的局域电场增强，从而提升了该谐振结构的介电传感灵敏度。所制备的生物传感器与切片介质样品如图9(b)。该传感器对不同的癌变细胞组织的具有不同的谐振响应，可以实现对浆液性卵巢癌（serous ovarian cancer）和卵巢透明细胞癌（ovarian clear cell carcinoma）组织切片的区分检测。



(a) Micrograph of a particle bound to the surface of the SLSP[90]

(b) Sliced samples on a glass slide (left) and the fabricated biosensor attached with a sliced sample (right)[87]

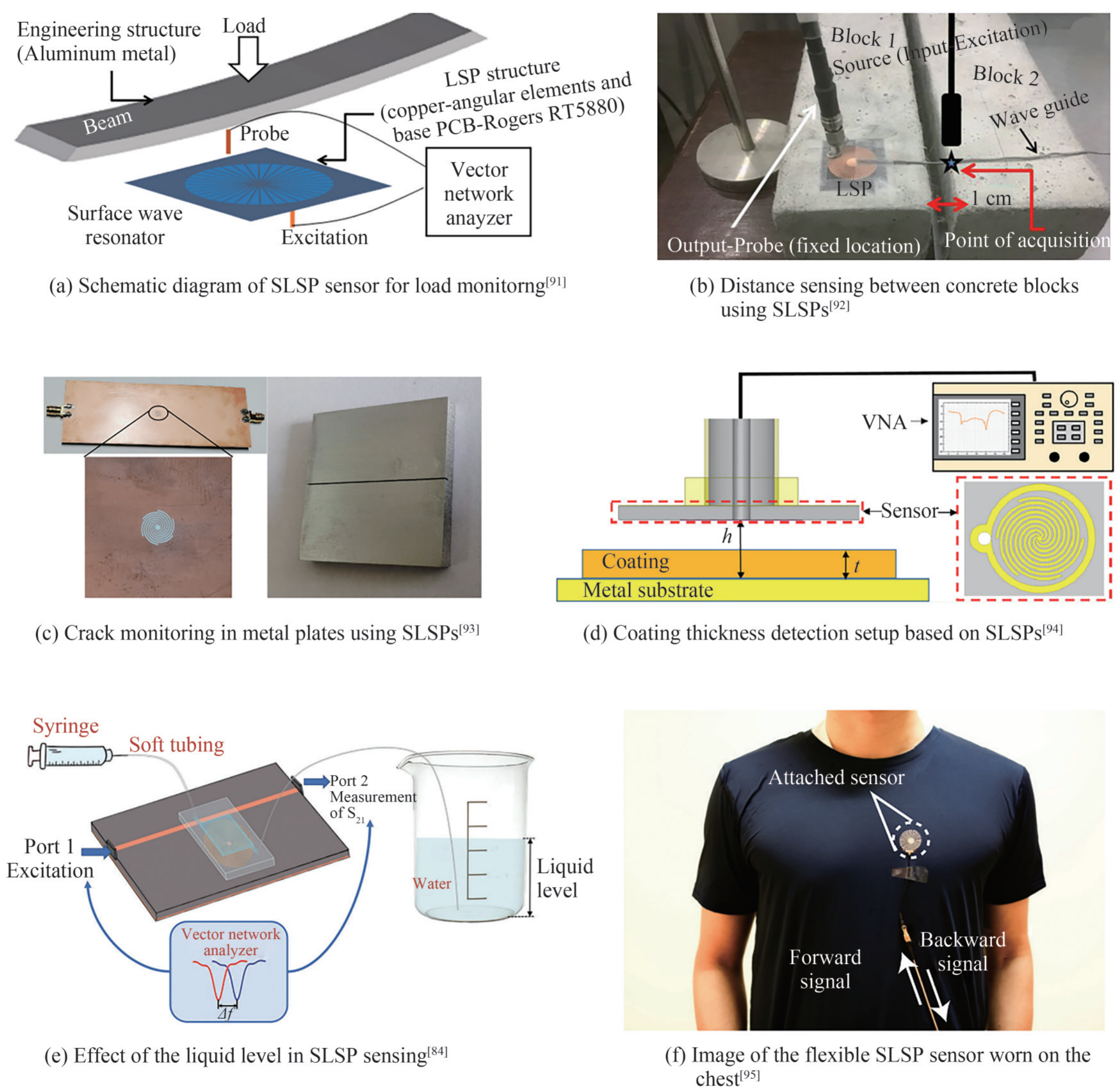
图9　基于人工局域表面等离激元的细胞传感[87,90]

Fig. 9　Cell sensing based on spoof localized surface plasmons[87,90]

3.3　基于人工局域表面等离激元的力学传感

印刷电路的介质基板在压力、拉力等作用下会产生形变，导致等效介电常数的变化，引起谐振峰频移。基于此原理，人工局域表面等离激元也可应用于力学量的传感，并用于柔性可穿戴设备中。2016年新加坡

南洋理工大学的SOH C K团队[91]通过非接触、近场测量的人工局域表面等离激元传感器，实现对工程结构横向（垂直于表面）载荷的测量，示意图如图10（a），载荷引起的金属条块形变会导致人工局域表面等离激元近场透射谱的变化。同年，该团队又研究了接触式人工局域表面等离激元传感器，可用于倾角、形变、间距等情况的测量[92]，图10（b）展示了该装置用于监测混凝土块之间距离的实验照片。2019年中国科学技术大学的孙利国团队提出了一种用于检测金属表面裂纹的人工局域表面等离激元传感器[93]，如图10（c）所示，并实验验证了该传感器对全向裂纹的检测能力。当检查一个具有0.2 mm宽和2 mm深裂纹的金属表面时，可以获得400 MHz的共振频移。2021年四川大学杨晓庆等[94]提出了一种基于人工局域表面等离激元来测量金属表面磁性吸波涂层厚度的方法，测量装置如图10（d）所示。实验结果表明：此种传感器可以检测0.05～1.03 mm范围的涂层厚度，误差达到6%以内。该传感器具有分辨率高、误差小、性能稳定等优点，并且对各种面积大小的涂层均可适用。2023年东南大学的崔铁军和张璇如团队[84]研究了液位对微波共振传感的影响，如图10（e）所示，液压压力影响微流腔材料的有效介电常数，从而引起额外的共振偏移信号。该工作研究了非接触和接触传感场景下液面高度带来的额外谐振频移信号，为微流环境下溶液传感的环境控制提供了指导。柔性可穿戴传感器是力学量传感的重要应用方向，可用于监测生理信号，跟踪疾病进展，在传统临床环境之外提供护理[78-83]，也是人工局域表面等离激元力学量传感的发展方向之一。2022年新加坡国立大学的HO J S团队[95]提出了一种由导电纺织物制成的人工局域表面等离激元传感器，如图10（f）所示。该传



(a) Schematic diagram of SLSP sensor for load monitorng[91]

(b) Distance sensing between concrete blocks using SLSPs[92]

(c) Crack monitoring in metal plates using SLSPs[93]

(d) Coating thickness detection setup based on SLSPs[94]

(e) Effect of the liquid level in SLSP sensing[84]

(f) Image of the flexible SLSP sensor worn on the chest[95]

图10 基于人工局域表面等离激元的力学量传感[84，91-95]

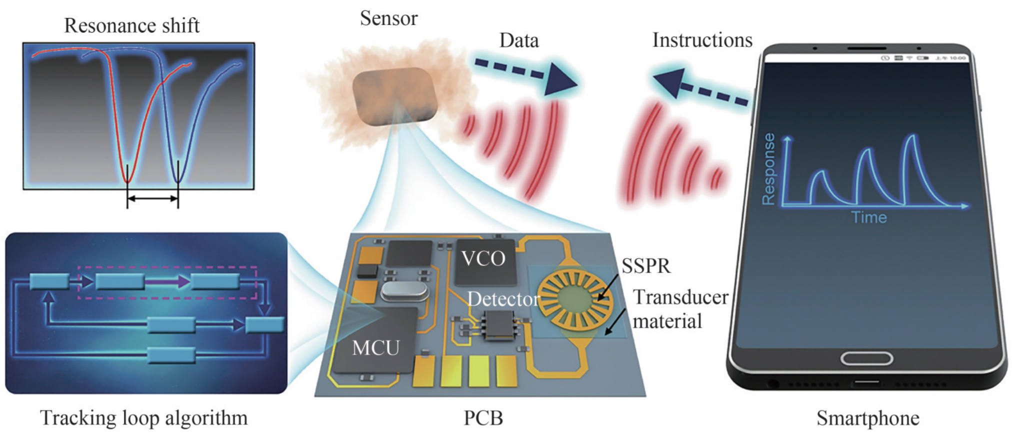
Fig. 10 Force sensing based on spoof localized surface plasmons[84，91-95]

感器可印刷于服装布料的表面，其谐振频率随人体表面的轻微起伏而变化，可实现对人体心跳和呼吸信号的实时检测。

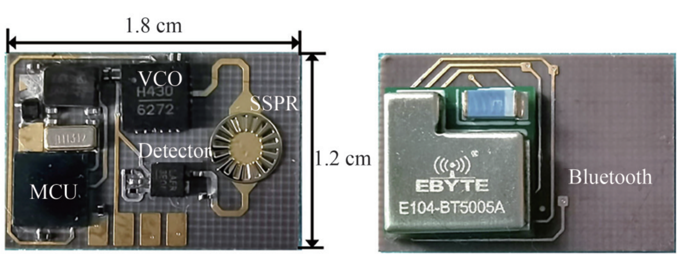
4　人工局域表面等离激元传感的系统集成

电磁谐振传感器对谐振峰频率的相对移动信号进行测量，相比于幅度或强度检测，易于获得更高的检测信噪比。然而，谐振峰频移信号的检测也更加复杂，现有的微波谐振传感大多依赖于矢量网络分析仪等台式仪器进行检测，小型化检测系统的研究方兴未艾。对于传统的叉指电极等微波谐振传感器，可以采用有源振荡和锁相环技术，将无源谐振信号转化为有源振荡信号，从而进行检测[96-98]。但深亚波长人工局域表面等离激元独特的振幅和相位响应，为有源振荡电路带来更大的挑战[99]。

2023年东南大学的崔铁军和张璇如课题组[100]提出并完成了一款小型化、智能化、无线物联的人工局域表面等离激元传感系统，如图11所示，其中(a)为该传感系统的示意图，(b)为该传感系统实物的正视和俯视照片，(c)为系统主要硬件的框图。该系统在1.8 cm×1.2 cm的电路板上集成了人工局域表面等离激元传感器、信号检测与处理电路、蓝牙通信模块，实现了传感信号的实时采集处理，并发送至手机端显示。该系统基于传统的Pound-Drever-Hall锁频技术进行改进[101-103]，在单片机中执行完成，以软件化的方式极大简化了检测电路[104, 105]。并且，锁频相关参数由初始的扫频过程自动计算获得，使得该传感系统可以实现对不同环境或不同检测目标的智能化自适应。软件化检测的方式可以方便地对传感信号进行实时的滤波降噪，最终实现了高达69 dB的信噪比和2 272 s^{-1}的高数据率。该工作中在人工局域表面等离激元谐振器表面贴附一层聚二甲基硅氧烷(Polydimethylsiloxane，PDMS)薄膜作为敏感材料，演示了其在易爆气体丙酮蒸汽传感中的应用。这套系统实现了高度的小型化，且取得了优异的信噪比指标，展示了人工局域表面等离激元在小型化、智能化、物联化传感技术中的应用潜力。



(a) Schematic of the ultracompact SLSP sensing system[100]



(b) Photographs of the ultracompact SLSP sensing system[100]

图11　人工局域表面等离激元小型化无线传感系统[100]

Fig. 11　Ultracompact and wireless SLSP sensing system[100]

5 总结与展望

从2012年人工局域表面等离激元传感提出至今的十多年里，该领域经历了高速发展，在新原理新现象持续涌现的同时，其小型化传感系统已初见雏形。万物互联时代对小型化、便携式传感技术的新需求，赋予了人工局域表面等离激元传感重要的实用价值和广阔的发展空间。

针对实际应用需求，人工局域表面等离激元传感领域面临着以下亟待解决的问题：1)持续挖掘人工局域表面等离激元微结构中可能存在的谐振新原理；2)持续突破传感相关指标，以满足实际传感的应用需要；3)致力于研究高精度、小型化的传感信号检测电路，推动小型化便携式传感系统的发展。最终，我们将实现小型化、物联化和高灵敏的传感系统，推进医疗、健康、环境等相关产业中传感技术发展升级。

在接下来的研究中，一方面迫切地需要面向生物医学、环境监测等实际应用需求，进行典型应用验证，明确人工局域表面等离激元相比于现有技术确有优势的应用场景，推动实质性的应用落地。另一方面，人工局域表面等离激元的结构设计仍然围绕提出初期的几种典型图形，人工微结构设计的灵活性尚未得到充分发挥，其中蕴含的新原理新现象也有待探究，并有望带来传感能力的大幅提升。因此，新物理研究和应用探索的同时进行和相互促进，还将是人工局域表面等离激元传感领域持续的发展趋势。

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Progress in Highly Sensitive Sensing Based on Spoof Localized Surface Plasmons (Invited)

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Abstract: Spoof Localized Surface Plasmons (SLSPs) are electromagnetic resonance modes in the microwave, millimeter-wave, and terahertz frequency bands, which can mimic the modal profiles and physical properties of optical localized surface plasmons based on plasmonic metamaterials. Due to the lower metal loss in these frequencies and the flexibilities in metamaterial designs, SLSPs can achieve excellent sensing characteristics such as deep-subwavelength field confinements, high quality factors, and high dielectric sensitivity. The SLSP concept was theoretically proposed by Pendry and Garcia-Vidal et al in 2012. In 2014, Cui et al proved that SLSPs can be sustained by ultrathin metal patterns on printed circuit boards, and envisioned SLSPs' applications in both the printed circuits and the integrated circuits. Meanwhile, the SLSPs can be integrated with passive and active lumped devices, and exhibit high flexibilities in integration with the signal detection circuits and the wireless communication circuits. Therefore, SLSPs present promising application potentials in compact and portable sensing systems for the internet of things.

This paper reviews the representative progress in recent years in the SLSP sensing area. In the first section, some novel resonance modes and resonance structures are introduced, with discussions on their promotions in the sensing indices. Hot topics such as plasmonic skyrmions, exceptional points, quasi-bound states in the continuum, and vortex mode are discussed here. Those novel SLSP electromagnetic modes provide new ideas for sensing. The spiral phase wavefronts of vortex waves can provide rich information and result in a high ability to detect multiple physical quantities. Novel resonance structures including fan-shaped ones, the three-dimensional ones based on origami metamaterials are introduced too, which provide new ideas and methods for SLSP sensor design. The resonance characteristics of SLSP in the terahertz band and its applications are also overviewed. Besides the widely studied array structures under space-wave excitation, it is an irresistible trend to develop terahertz sensing in semiconductor integrated circuits. SLSP sensors pioneers the way for the development of on-chip terahertz biosensing systems. In the second section, the sensing enhancement techniques based on mode coupling and active amplifiers are discussed. Hot spot structures where electromagnetic energy converges can be constructed based on mode coupling inside SLSPs, and can result in highly sensitive hybridization modes. Loading active amplifiers can effectively compensate for the losses in the sensing structure and can improve the quality factor and the excitation efficiency. These techniques supply reliable solutions for the improvements of SLSP sensing indices. Then, typical application scenarios of SLSP sensing are introduced, ranging from solution concentration sensing, bacteria and cancer cell sensing, and mechanical sensing based on flexible SLSP circuits. SLSP can compress the microwave electromagnetic resonances into a deep sub-wavelength scale, greatly enhance the sensing sensitivity to tiny biomedical targets, and break the bottleneck of microwave resonance sensing limited by long wavelengths. Finally, we introduce a recently reported SLSP sensing system, which integrates the SLSP sensor with its signal detection circuits and the Bluetooth module into an ultra-compact size of 1.8 cm×1.2 cm. The signal-noise ratio of this ultracompact sensing system can reach a high value of 69 dB and the system is validated by explosive acetone vapor sensing.

The review paper ends with prospective discussions of the SLSP sensing development. Novel principles and phenomena still emerge continuously in the SLSP area, while ultra-compact sensing systems have been constructed yet. We believe that it is good timing now to land the SLSP concept on practical applications. In the following research, there is still a large space for both scientific research and application explorations of SLSP sensing. The mutual promotion of scientific and engineering investigations will surely stimulate the continuous development of SLSP sensing.

Key words: Electromagnetic resonances; Spoof localized surface plasmons; Sensing enhancements; Sensing sensitivity; Sensing systems

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