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面向智能感知的超表面辅助无线定位方法

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摘要 高精度感知定位作为现代智能系统的关键技术，其集成化发展受到分立式天线架构的严重制约. 基于传统超表面的感知系统因依赖额外的馈源喇叭和接收天线，难以同时满足小型化和高性能要求. 本文提出了一种面向智能感知的超表面辅助无线定位方法, 创新性地将环形器与超表面天线融合, 实现了高度集成的全双工设计. 该方案采用线性调频(linear frequency modulation, LFM)信号作为载波，利用其频率时变特性解决了收发信号空间相位叠加导致的波形失真问题. 实验结果表明, 所构建的系统在3 m探测范围内实现了15°的分辨精度, 并可检测到大于0.02的回波强度变化. 与现有技术相比，该系统体积缩减80%以上，在保证定位性能的同时显著提升了集成性和稳定性. 这一突破性设计为开发紧凑型高性能感知系统提供了新思路，在智能家居、安防监控和雷达探测等领域具有重要的应用价值.

关键词 信息超表面, 收发一体, 智能感知, 定位系统

天线作为电磁波调控的核心器件，在现代通信、雷达探测和微波成像等领域发挥着关键作用[1~3]. 传统天线阵列及相控阵技术依赖复杂的硬件架构和精细的算法控制，面临成本高、能效低和便携性差等挑战[4,5]. 超表面通过将亚波长单元结构进行梯度排列，可实现对电磁波前的精确调控[6,7]. 然而，传统超表面存在功能固定、无法动态重构等局限，难以满足复杂多变的实际应用需求[8,9]. 信息超表面通过集成可调元件和现场可编程门阵列(field programmable gate array, FPGA), 能够实时调控电磁波的幅度、相位和偏振参数，为构建智能电磁环境提供了关键技术支撑[10~15].

在智能感知领域，信息超表面凭借低损耗和快速可编程等技术优势，显著提高了定位的精度与分辨率[16~18]. 例如，Huang等人利用信息超表面构建虚拟视距路径，解决了传统近场定位方法在非视距环境下性能下降的问题[19]. Zhang等人提出了一种信息超表面辅助的室内多用户定位方案, 通过优化信号空间分布, 使定位精度提升50%以上[20]. 进一步地, 结合人工智能和机器学习算法，Li开发了基于信息超表面的智能感知系统，采用多层卷积神经网络实现了目标区域定位、手语识别和呼吸监测[21]. Wan团队设计了基于稀疏贝叶斯学习的SBLNet架构，通过提取接收数据的非线性关联特征，在低信噪比环境下对高速移动目标的识别分辨率提升了约15%[22]. 尽管上述研究实现了低成本、高效率的目标识别与定位，但现有基于信息超表面的感知定位系统通常需要额外的馈源喇叭和接收天线[23~26]. 这不仅增加了系统的复杂度和成本, 还对其小型化和集成化应用造成了阻碍. 此外, 还有一些研究通过在超表面上加载传感器件来实现感知探测[27~29]. 例如，Jiang等人通过集成功率传感器实现了目标定位和

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波束自适应调控, 但也因功率检测器的引入而增加了成本和功耗[30]. 这些问题使得当前系统在成本控制、集成度和能效方面面临严峻挑战. 因此, 亟需探索一种低成本、高集成度、低功耗, 并能实现信号收发一体化的感知定位方法.

本文提出了一种面向智能感知的超表面辅助无线定位方法. 该方法创新性地将可重构信息超表面天线与环形器进行集成设计, 实现了收发一体化架构. 通过采用线性调频(linear frequency modulation, LFM)信号作为载波, 解决了单频连续信号在传输过程中面临的同频干扰难题, 大幅提升了反射回波的可检测性. 所研制的超表面天线通过调控PIN二极管状态可实现60°范围内的双波束动态扫描, 并且兼具低剖面、低损耗和高增益等特性. 以该超表面为核心搭建的雷达收发一体化定位系统, 仅使用通用软件无线电外设(universal software radio peripheral, USRP)进行信号生成和处理, 在3 m范围内实现了15°的方位分辨精度. 该系统摆脱了传统感知定位方法对馈源喇叭和接收天线的依赖, 在增强其紧凑性的同时进一步提升了定位系统的稳定性, 展示出低成本、结构简单、易于部署等优势.

1 收发一体化定位系统设计

针对传统信息超表面感知系统在硬件架构上存在的激励源依赖性和接收天线分立性等问题, 提出了一种基于信息超表面天线的收发一体化定位方法. 信息超表面将平面阵列天线作为激励源并与高隔离度环形器集成, 避免了系统对馈源喇叭和接收天线的额外需求, 提升了硬件平台的紧凑性与集成度. 如图1所示, 系统采用分层式控制方式实现智能波束调控: 上位机(personal computer, PC)基于相位梯度理论生成最优波束赋形编码序列, 数字控制器驱动FPGA输出可编程电平对超表面辐射角度进行调控. 在信号生成方面, 系统使用USRP产生LFM信号, 对平面阵列天线进行激励. 在信息超表面和平面阵列天线的协同调控下, 系统生成具有空间-时间-频率多维耦合特性的扫描波束. 得益于LFM信号固有的时频调制特征, 回波信号能够被集成化天线系统有效接收. 在接收链路中, 回波信号经环形器分离被传输至USRP进行数字化采样, 通过瞬态信号检测、参考电平分析等处理流程, 最终实现对目标位置的精确检测.

图2(a)展示了本研究所采用的集成化超表面天线实物[31]. 超表面由16单元线阵构成, 同属一个线阵的单

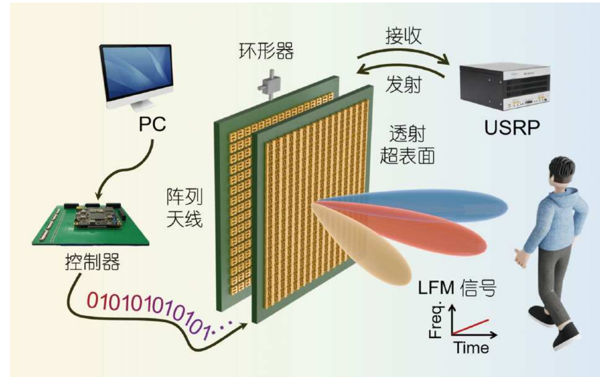

图 1 (网络版彩色)基于信息超表面天线的雷达收发一体化定位架构

Figure 1 (Color online) Schematic of the radar localization method with receive-transmit integration characteristics based on information metasurface antenna

元由超表面控制器提供同步偏置电压. 平面阵列天线共包括16×16个单元, 通过功分馈电网络实现均匀激励, 从而在超表面区域形成等效平面波照射. 超表面和阵列天线的单元尺寸均为15 mm, 单元采用均匀排布方式, 间距为15 mm. 为验证超表面天线的波束调控性能, 选取典型方位角0°、±15°、±30°、±45°、±60°在5.8 GHz进行辐射特性测试. 如图2(b)所示, 该超表面天线在±45°扫描范围内的实测最大指向误差不超过2.5°, 同时保持优于–10 dB的副瓣抑制; 当扫描角度扩展至±60°时, 虽然波束指向误差增大至7°, 但副瓣抑制水平仍能稳定维持在–14.1 dB. 测试结果表明, 该超表面天线在宽角度扫描范围内兼具指向精度与副瓣抑制能力, 在雷达探测和无线通信系统中具有重要应用价值.

现有的超表面感知系统通常需要额外的喇叭天线作为接收, 不仅增加了系统体积和复杂度, 更严重制约了其在空间受限场景中的应用. 根据天线互易性原理, 所研制的超表面天线具备与发射性能相当的接收能力, 这为实现收发一体化设计提供了理论基础. 然而, 在5.77~5.83 GHz的窄带工作条件下, 频分复用和时分复用等传统收发一体化方案存在明显局限性: 频分复用方案难以满足定位应用需求, 而时分复用方案则受限于切换时延, 在探测距离过近或过远时均无法有效接收回波信号. 环形器是一种三端口非互易器件, 通过端口间的定向传输特性可辅助天线实现信号同时收发. 因此, 本研究提出将高隔离度射频环形器与超表面天线集成的收发一体化方案. 实验采用50 Ω同轴负载和矢量网络分析仪对环形器在5.5~6.0 GHz频段的性能进

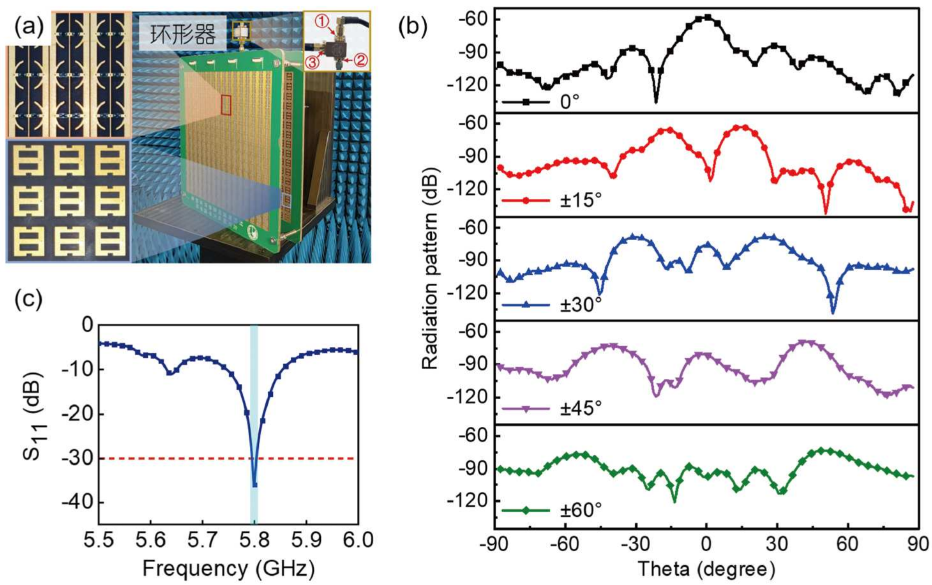

图 2 (网络版彩色)超表面天线实物及辐射特性测试结果. (a) 超表面天线实物图. (b) 远场辐射方向图. (c) 集成环形器后的反射系数曲线
Figure 2 (Color online) Metasurface antenna prototype and radiation characteristics test results. (a) Metasurface antenna prototype. (b) Far-field radiation pattern. (c) Reflection coefficient after integrating circulator

行了测试，结果表明其在整个频段内插入损耗均低于0.5 dB, 在5.8 GHz处端口隔离度优于30 dB. 如图2(c)所示，集成环形器后的超表面天线在5.796~5.804 GHz工作频段内反射系数S_{11}显著低于–30 dB，具有高效的辐射性能．这些结果充分验证了该集成化设计方案对于维持天线高效辐射和实现自发自收的可行性.

在集成化超表面天线设计基础上，提出了一种基于收发一体化超表面天线的目标定位方法，其原理如图3所示．以±45°探测为例，发射信号通过环形器1端口激励天线产生±45°方向的定向辐射，当电磁波照射到–45°方位的人体目标时，其反射回波被超表面天线接收并经环形器3端口传输至信号处理终端．然而，传统单频连续信号在实际应用中存在显著局限性，主要表现为收发信号的空间相位叠加导致的波形失真，以及环形器有限隔离特性引发的收发串扰．这些问题严重恶化了信号质量，大幅降低了系统的探测稳定性．为克服同频干扰对系统探测性能的影响，基于USRP硬件平台100 kHz的瞬时带宽限制，设计了带宽50 kHz、脉宽0.25 ms、调频斜率为200 kHz/ms的LFM波形. 该波形具有频率时变特性, 能够实现发射信号与反射回波在频域的有效分离，从而规避了同频干扰的影响，为天线在复杂电磁环境下的稳定探测提供了可靠保障.

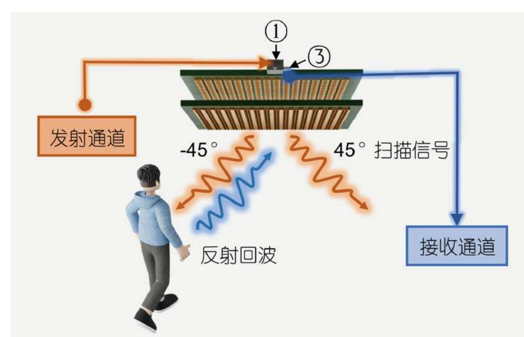

图 3 (网络版彩色)基于收发一体化超表面天线的目标探测原理
Figure 3 (Color online) Target detection principle based on the metasurface antenna with receive-transmit integration characteristics

2 定位系统搭建与性能验证

以集成化超表面天线为核心搭建的感知定位系统的实验平台及其定位流程如图4和5所示. 系统包含PC、FPGA控制板(Xilinx XC7Z020-2CLG484I)、USRP(路光电子SDR-LW 2974)和信息超表面天线. 根据每个部分的功能，系统可划分为编码控制、信号收发和信号处理3个核心模块．编码控制模块包含PC和FPGA控制板，PC负责计算最优波束赋形编码，FPGA生成0/3.3V可编程偏置电压驱动超表面进行波束调控．信号发射与接收模块由USRP、环形器与超表面天线级联构成,

用于LFM信号的生成、发射以及目标回波信号的采集. 信号处理模块采用环境自适应算法实现目标检测与定位. 系统通过采集无人场景回波信号建立高、低参考电平环境基准, 实时测量当前场景信号电平后, 计算其与环境基准的差分波动特征量. 基于预设阈值判别机制, 当特定波束指向角度的信号波动量超过阈值时即判定该方位存在目标, 否则为无人状态.

图6(a)和(b)分别展示了信息超表面天线在0°编码状态下发射的LFM信号的时域波形及时-频分布. 实验数据采集时长为1.25 ms, 包含5个完整信号周期. 测量结果显示, 发射信号的频率随时间呈严格的线性变化特性: 在0.25 ms时间范围内, 频率从初始0 Hz线性增长至50 kHz, 调频斜率为200 kHz/ms, 与理论设计参数吻合. 接收到的反射回波及其对应的时-频曲线如图6(c)和(d)所示. 接收信号与发射信号的时域波形相似, 但受到传播路径损耗和反射界面损耗影响, 导致出现约0.25 ms的时延与60%的幅度衰减. 而且, 接收信号保持了200 kHz/ms的调频斜率, 证实了信息超表面天线在信号生成与反射过程中的稳定性, 为高精度目标探测和定位系统的实现提供了强有力的硬件支撑.

为了验证所提出智能感知系统设计方案的有效性, 对3 m范围内的移动人员进行了探测. 超表面天线使用5种编码方式, 分别发射0°、±15°、±30°、±45°、±60°的空间扫描信号进行目标探测, 并接收其回波信息. 图7(a)展示了无人情况下的环境反射, 其强度约为0.38. 当人在0°探测范围内走动时, 其他角度的回波信号波动值稳定维持在0.001以下, 而在0°处信号产生剧烈波动, 波动幅度达到0.08, 如图7(b)所示. 同样地, 当探测目标位于15°与45°时, 探测回波仅在对应角度产生明显

图 4 (网络版彩色)定位系统实验平台

Figure 4 (Color online) Experimental platform of the proposed positioning system

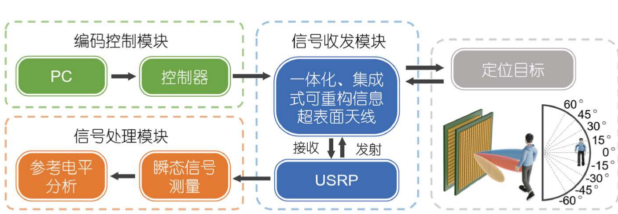

图 5 (网络版彩色)感知定位系统的定位流程示意

Figure 5 (Color online) Schematic diagram of the positioning process of the sensing and positioning system

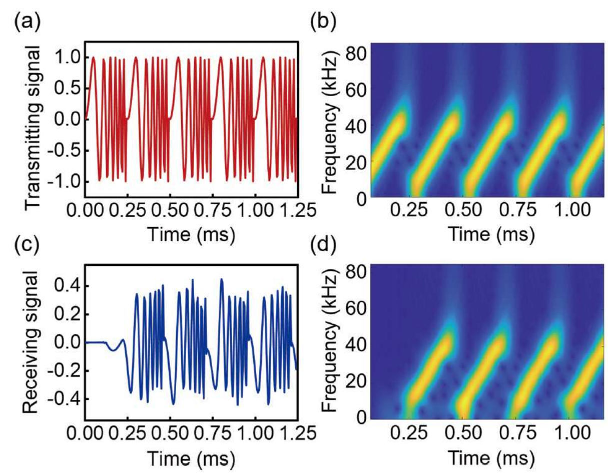

图 6 (网络版彩色)发射与接收的LFM信号. (a) 发射信号的时域波形. (b) 发射信号的时频图. (c) 接收信号的时域波形. (d) 接收信号的时频图

Figure 6 (Color online) Transmitting and receiving LFM signals. (a) Time-domain waveform of the transmitting signal. (b) Time-frequency diagram of the transmitting signal. (c) Time-domain waveform of the receiving signal. (d) Time-frequency diagram of the receiving signal

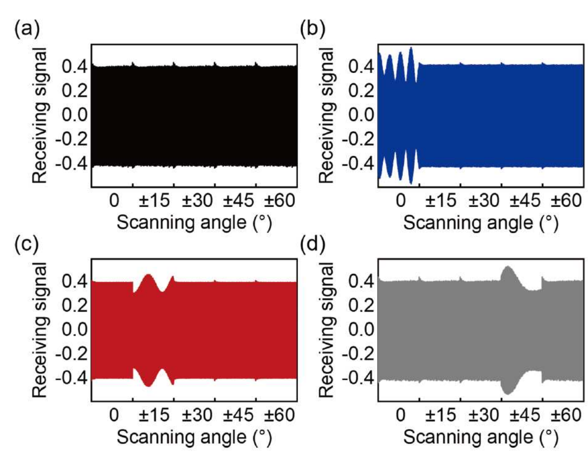

图 7 (网络版彩色)定位系统接收到的反射回波强度. (a) 环境反射. (b) 0°目标探测. (c) ±15°目标探测. (d) ±45°目标探测

Figure 7 (Color online) Reflected echo wave intensity received by the positioning system. (a) Environmental reflection. (b) Target detection at 0°. (c) Target detection at ±15°. (d) Target detection at ±45°

的波动, 且幅度大于0.03, 如图7(c)和(d)所示. 实验后续对5个角度的回波探测能力进行了多次重复测试, 在移动人员出现的角度信号明显波动, 且波动幅度稳定大于0.02. 基于该阈值, 通过对超表面加载动态扫描编码有望实现±60°范围内实时目标监测. 实验搭建的雷达收发一体化定位系统, 摆脱了对馈源喇叭和接收天线的依赖, 实现了高集成、低偏差、快速响应的回波定位. 加载动态扫描编码的设计进一步提升了系统的普适性与实用性, 在智能家居、健康监护和自动驾驶等领域展现出广阔的应用前景.

3 结论

本研究提出了一种面向智能感知的超表面辅助无线定位系统, 该系统集成了结构紧凑、工作稳定等优势, 可实现高可靠和快速的目标探测. 超表面天线使用平面阵列天线代替传统喇叭作为激励, 有效降低了天线剖面. 基于PIN二极管设计的可重构超表面通过编码状态切换, 支持±60°范围内的动态波束扫描. 与环形器集成后, 天线在工作频点稳定保持小于−10 dB的回波损耗, 以及30 dB以上的收发隔离度. 对搭载LFM信号的集成化天线进行测试, 结果表明系统可实现稳定的自发自收, 且在3 m探测范围内可达到15°分辨精度. 结合超表面动态调控性能提出的自发自收实时探测方案, 为智能家居、安防监控等应用场景中的便携式感知设备发展开辟了新途径.

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Summary for “面向智能感知的超表面辅助无线定位方法”

Metasurface-assisted wireless localization method for intelligent sensing

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Electromagnetic intelligent sensing, as a contactless and non-invasive sensing paradigm, has been widely applied in diverse fields such as intelligent home, autonomous driving, and smart surveillance. Currently, most intelligent sensing systems rely on massive antenna arrays, which suffer from high cost, low energy efficiency, and limited portability due to their complex hardware architectures and sophisticated control algorithms. Information metasurface, with low cost, minimal loss, and rapid reconfigurability, has emerged as a promising alternative, offering dynamic control over amplitude, phase, and polarization of electromagnetic waves through integrated tunable elements and field-programmable gate array. However, conventional metasurface-based sensing systems still require additional electromagnetic components such as feed horns, receiving antennas, and power sensors, which fundamentally limit their miniaturization and working performance. Consequently, there is an urgent need to develop novel sensing and localization methods that simultaneously satisfy the requirements of low cost, low power consumption, and high integration characteristics.

In this study, an innovative radar localization method with receive-transmit integration characteristics is proposed by utilizing a programmable information metasurface antenna, to address the critical limitations of the dependence on external excitation sources and receiving antennas. The proposed metasurface employs a planar array antenna as the excitation source, maintaining the desirable characteristics of low profile, minimal loss, and high gain performance, and can achieve dynamic dual-beam scanning within a 60° range by controlling PIN diode states. Based on the reciprocity theory, a receive-transmit integration design of metasurface antenna is realized by incorporating a high-isolation circulator. This design remains the original radiation performance while effectively eliminating signal interference between transmission and reception channels in single-path operation. Furthermore, to mitigate the adverse effects of spatial phase superposition between transmitted and reflected waves, a linear frequency modulation (LFM) signal with time-varying frequency characteristics is introduced as the system excitation. According to the antenna’s –30 dB bandwidth, the designed LFM waveform features 50 kHz bandwidth and 0.25 ms pulse width, significantly enhancing the signal-to-noise ratio and detectability of reflected waves. Leveraging the integrated metasurface antenna design, a radar receive-transmit integration system is constructed for target localization. During operation, the high and low signal levels in the current scenario are continuously monitored and their fluctuation characteristics are calculated relative to the environmental baselines, which are established by collecting reflected waves in target-free environments. Through the threshold detection algorithm, the target is identified when the signal variation at specific orientation surpasses the predetermined threshold value. To evaluate the localization accuracy of the proposed system, experimental validation is performed by detecting moving human subjects within a 3 m range. The metasurface antenna employs five distinct coding schemes to generate spatially scanning beams at 0°, ±15°, ±30°, ±45°, and ±60°. Experimental results demonstrate that the system achieves observable signal intensity variations exceeding 0.02 at a 3 m detection range with 15° angular resolution. Furthermore, by using the minimum signal variation amplitude at each angle as the detection threshold, real-time target monitoring within ±60° can be achieved by loading dynamic coding sequences.

In summary, this work presents a localization system with low cost, low power consumption, and receive-transmit integration characteristics by integrating programmable metasurface antenna with high-isolation circulator and utilizing LFM signal. This design provides a novel approach for developing compact high-performance sensing systems, exhibiting significant potential in diverse applications such as smart home automation, healthcare monitoring, and autonomous driving.

information metasurface, receive-transmit integration, intelligent sensing, positioning system

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