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博士学位论文

中文论文题目：基于多向相干声表面波的微粒可重构操控理论及
方法研究

英文论文题目：Study on Theory and Methodology of
Reconfigurable Particle Manipulation by
Multidirectional Coherent Surface Acoustic Wave

摘要

微操控技术以其精准调控能力,在单细胞分析、靶向递送等领域展现出独特优势。声学操控技术凭借其非侵入与高定位精度等特性,成为突破传统光镊的高强度激光因局部能量沉积导致的细胞损伤问题与磁控材料通常具有铁磁或顺磁特性局限的前沿方向。来自不同方向相互干涉的声场作为声镊技术的核心载体,其动态重构能力直接决定了操控的维度。近年来,基于声表面波的微粒操控技术凭借其微米级操控精度与低热损伤特性,得到了广泛的研究与关注。然而,目前声表面波操控技术依旧存在以下问题:现有研究对多向相干声表面波场的拓扑重构规律及动态调控理论鲜有研究,制约了可重构操控技术的发展;声表面波微粒操控方法因驻波模式的静态排布局限与行波模式的声流场失稳,导致实时运动调控能力不足;此外现有技术在生物细胞操控应用中受限于操控分辨率限制及声阻抗差异,导致复杂微环境下生物体细胞的操控能力受限。为此,本学位论文通过建立多向相干声表面波重构理论模型,研究驻波场势阱动态重构与行波场声流涡旋演化特性;基于多向相干对称性布局与衬底各向异性完成了微粒操控装置设计与制造;建立“频率-幅值-相位”多参数动态调控框架,实现了微粒集群排布向聚集体运动轨迹切换的递进式操控;并基于行波与驻波的分时复用策略,实现小型模式生物体内细胞捕获与动态重构。本文主要研究内容如下:

(1) 针对当前声操控理论难以分析动态声场拓扑形貌实时重构过程的局限,构建了多向相干声表面波可重构操控理论模型,分析了相干波激发过程中的传播及分布特征。研究了各向异性压电材料中声表面波的椭圆偏振位移及能量局域化特性,通过分析驻波场微粒响应机制,阐明了其受控组装规律,并开展了相干驻波调控的声势阱形貌动态重构过程分析。结合 Navier-Stokes 方程描述了声流涡旋的生成机制,通过声流场中微粒多向力平衡方程的推导,建立了声流场涡旋拓扑结构与微粒轨迹间的映射关系。

(2) 针对传统换能器阵列设计中衬底各向异性导致的声场畸变,提出了一种耦合衬底各向异性的多向相干微粒操控装置结构设计,确保了声能的均匀激发与精确控形,并实现了装置的加工制造与测试。基于压电材料特性优化换能器参数,并通过施加声阻抗与位移边界约束条件,模拟了声场传播过程以验证参数有效性。基于对称性约束与衬底各向异性设计了微粒操控装置,实现了声能均匀传输及相位同步调控。基于微

纳加工中的光刻-薄膜沉积-键合工艺链,实现了多向相干声表面波微粒操控装置的掩模版制备、换能器制造及微流控腔室加工,并完成了装置的集成与声学性能测试。

(3) 针对多向相干驻波场参数与波矢构型的精确调控难题,提出了多向相干驻波操控的微粒排布可重构操控方法,实现了微粒集群与聚集体排布阵列及形貌的精准操控。建立了驻波参数与微粒集群空间分布的映射模型,分析了相干驻波场中微粒分布特性,通过波矢构型与相位差调控实现六方晶格/斜向阵列等多模态排布;建立声场参数(频率-相位-幅值)动态调控策略,实现集群平移/旋转及阵列密度重构;开发多通道换能器协同驱动技术,实现阵列同步操控(排布间距误差 $<5\%$);阐明声压梯度与二次辐射力协同作用机制,实现聚集体构型快速切换与拓扑重构。

(4) 面向复杂流道环境中的微粒运动操控需求,提出了多向相干行波叠加的微粒轨迹动态操控方法,揭示了声流场分布对轨迹的调控规律,实现了从单微粒向集群递进的运动调控与轨迹切换。通过相干行波场调控实现了单分散微粒快速富集($<6\text{ s}$)及多分散微粒高效分选(纯度 $>90\%$)。明确揭示了微粒轨迹对声场参数的响应规律,实现了运动轨迹精准调控。揭示了声流动量传递与构型演变的耦合机制,通过实时声场调谐实现了聚集体稳定旋转(最高转速 360 rpm)与轨迹实时操控。

(5) 面向生物体内复杂血流环境下细胞捕获与操控的挑战,采用相干行波与驻波的分时复用动态调控策略,实现了小型模式生物—斑马鱼体内细胞的高效可重构操控与血流动力学干预。搭建了多向相干声场细胞操控平台,验证了驻波与行波场对细胞的体外动态操控能力,实现了细胞群高通量富集与分选,以及运动轨迹的动态切换与集群阵列重构。通过驻波-行波分时复用策略以及阻抗匹配界面,在斑马鱼胚胎血管内构建动态声势阱,实现了脉动血流下细胞可重构捕获(单/双节点)与血流动力学调控(流速 $0\sim 487\pm 18\text{ }\mu\text{m/s}$)。

关键词: 相干声表面波; 声场可重构理论; 微粒操控装置; 相干操控方法; 细胞操控实验

Abstract

Micromanipulation technology has shown unique advantages in single-cell analysis, targeted delivery and other fields with its precise regulation ability. Acoustic manipulation technology, with its non-invasive and high-positioning accuracy, has become a frontier direction to break through the problem of cell damage caused by localized energy deposition of high-intensity laser in traditional optical tweezers and the limitations of magnetron materials, which usually have ferromagnetic or paramagnetic properties. As the main support of acoustic tweezers, the dynamic reconstruction ability of the interfering acoustic fields from different directions directly determines the dimension of the manipulation. In recent years, particle manipulation based on surface acoustic waves (SAW) has been widely researched and paid attention to by virtue of its micrometer-level manipulation accuracy and low thermal damage characteristics. However, the following problems still exist in the current SAW manipulation technology: there are few studies on the topological reconstruction law and dynamic regulation theory of the multidirectional coherent SAW field, which constrains the development of the reconstructible manipulation technology; the SAW particle manipulation method has insufficient real-time motion regulation ability due to the static arrangement limitation of the standing wave mode and the acoustic current field instability of the traveling wave mode; and the existing technology has been limited by the limitation of manipulation resolution for the application of biocellular manipulation. In addition, the existing techniques in biological cell manipulation are limited by the limitation of manipulation resolution and acoustic impedance difference, which results in the limited ability to manipulate biological cells in complex microenvironments. We have established a theoretical model of multidirectional coherent surface acoustic wave reconstruction, and investigated the dynamic reconstruction of standing-wave field potential wells and the characteristics of acoustic vortex evolution in traveling-wave fields. A multi-parameter dynamic control framework of “frequency-amplitude-phase” is established to realize the progressive manipulation of the particle cluster arrangement to the switching of the aggregation trajectory; and based on the time-multiplexing strategy of travelling wave and standing wave, the capture and dynamic reconstruction of the cells in the organism are realized. The main research contents include:

- (1) A theoretical framework for particle reconfigurable manipulation using

multidirectional coherent SAW is proposed. The propagation characteristics and spatial distribution properties of coherent wave excitation are analyzed to predict particle trajectories and reconfiguration trends. Elliptical polarization displacement and energy localization of SAW in anisotropic piezoelectric materials are revealed, and the controlled assembly law is elucidated through the dynamic equilibrium mechanism of particles in standing-wave fields. Dynamic reconstruction of acoustic potential wells is realized through multidirectional coherent standing-wave modulation. The spatial-temporal evolution characteristics of acoustic vortices are analyzed using the Navier-Stokes equation, establishing a quantitative mapping relationship between vortex topology and particle trajectories by constructing multidirectional force balance equations and coherent weight models.

(2) Parameter optimization and boundary condition analysis for transducer units are conducted, and multidirectional coherent SAW device structures are designed, fabricated, and integrated. Transducer parameters are optimized based on piezoelectric material properties, and acoustic pressure field distributions are predicted through acoustic impedance and velocity boundary constraints. Symmetry constraints and anisotropy compensation strategies are adopted to design multidirectional coherent SAW device, achieving acoustic energy localization and phase synchronization regulation. A three-way symmetric eccentric transducer array is constructed to induce dynamic acoustic vortex fields, improving acoustic energy flow density uniformity and flow field reconstruction capability. Device fabrication is completed using cross-scale processing systems, and efficient integration is realized through plasma activation.

(3) A reconfigurable particle arrangement manipulation method based on multidirectional coherent standing-wave regulation is proposed. A mapping model between standing-wave parameters and cluster spatial distributions is established, enabling dynamic reconfiguration of cluster arrays and real-time cluster morphology switching. Particle arrangement laws in coherent standing-wave fields are revealed, achieving multimodal arrangements such as hexagonal lattices and diagonal arrays by regulating wave vector configurations and phase differences. A dynamic acoustic field parameter regulation strategy (frequency-phase-amplitude) is established, realizing cluster translation, rotation, and array density reconfiguration. Multi-channel transducer co-driving technology is developed, achieving synchronous array manipulation (spacing error $< 5\%$). The synergistic mechanism

of acoustic pressure gradients and secondary radiation forces is elucidated, enabling rapid switching of cluster configurations and topological reconstructions.

(4) A reconfigurable particle trajectory manipulation method based on multidirectional coherent traveling-wave superposition is proposed. The regulation of particle trajectories by acoustic flow field distributions is revealed, achieving progressive motion regulation and trajectory switching from clusters to single particles. Coherent traveling-wave field regulation enables rapid enrichment (< 6 s) of monodisperse particles and efficient sorting ($> 90\%$ purity) of polydisperse systems. A dynamic mapping relationship between acoustic field parameters and particle trajectories is established, realizing precise trajectory control. The coupling mechanism between acoustic flux transfer and configuration evolution is revealed, achieving synchronized control of stable spinning (up to 360 rpm) and trajectory reconstruction of aggregates through real-time acoustic field tuning.

(5) In-vitro acoustic manipulation of cell samples is conducted, and real-time cell reconstruction and manipulation in zebrafish are achieved through coherent traveling-wave and standing-wave time-multiplexing strategies. A multidirectional coherent acoustic cell manipulation platform is established, verifying dynamic cell manipulation by standing and traveling-wave fields. High-throughput enrichment and sorting of cell populations, dynamic trajectory switching, and clustered array reconstruction are realized. Dynamic acoustic potential traps are constructed in zebrafish embryonic blood vessels through the synergistic “standing-wave/traveling-wave time-multiplexing” mechanism, achieving dual-mode trapping of blood cells (single/two-node) and hemodynamic regulation (flow rate $0\text{--}487\pm 18$ $\mu\text{m/s}$) under pulsatile blood flow.

KEYWORDS: Coherent surface acoustic waves; Acoustic field reconfigurable theory; Particle manipulation device; Coherent manipulation method; Cell manipulation experiment