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声学超材料: 展望未来

沈平

香港科技大学物理系和高等研究院, 香港 999077
E-mail: sheng@ust.hk

声学超材料诞生至今已有25年. 在此期间, 声学超材料已从一个新奇的科学概念发展成一个活跃、多样的研究领域. 目前, 声学超材料的研究覆盖了众多方向, 其参与者来自各个不同学科. 值此之际, 我们自然要问: 这些研究将带领我们走向何方? 诚然, 对未来的预测总是存在风险, 但过往科学的发展轨迹为我们对未来的展望提供了指引.

我们不妨追溯半导体和液晶这两种影响深远的科技发展史. 以半导体的发展为例, 固态晶体管的发明最初源于利用掺杂来局域调制电学特性的这一科学发现. 这一由材料物理学到技术突破的跨越, 不仅对微纳尺度设备的技术进步具有重要意义, 还对介观物理学中诸多领域的诞生和发展起到重要作用. 再看液晶的发展, 也是与半导体类似的过程: 该领域始于科学家对新奇物态中的位置序和取向序的关注, 继而发展为取向序与光相互作用的电操控技术, 最终推动了液晶显示技术的发展. 该历程成为软物质物理学的两大范式之一(另一范式为高分子聚合物).

上述两个案例的共同特点在于对基础研究应用潜力的商业化. 其进程始于对新奇物理现象的关注推动了技术突破, 并最终实现低成本产品的工业化生产. 而这些产品或是能为传统手段束手无策的问题提供解决方案, 或是能通过新奇的功能激励新的消费需求. 这一商业化流程也可直接或间接地为后续研发活动提供资金支持, 因而至关重要. 与之相较, 有些科学发现昙花一现, 它们在短期内有不少令人振奋的结果, 但未能实现商业化应用, 而后续的研发活动因此减少, 最终整个领域也随之逐渐式微.

声学超材料基于微观的亚波长几何结构与宏观的波动物理学的有机结合, 为声波调控提供丰富的解决方案. 该领域目前正处于商业化的初级阶段——各种传统手段无法实现的功能, 如声音的完美吸收, 正被不同程度地商业化. 我希望特别关注三个领域: (1) 纳米声子学. 当局域共振单元缩小至纳米尺度时, 其声子统计学性质及其他一系列弹性和热学特征都将发生改变, 从而产生新奇的物理现象与应用[1]. (2) 水声学. 在所有的声学研究领域中, 如果单论已发表科学论文及新发明的数量, 水声学中的超材料发展似乎相对缓慢. 遥遥领先的前两位则分别是: 凭借研究成熟度和应用商业化程度独占鳌头的超声学, 以及因声学超材料兴起而复兴的空气传播声学和电声学. 让人欣慰的是, 最近水声超材料的研究正在飞速崛起[2]. (3) 利用薄样品调控百赫兹以下的低频空气声波. 这个领域目前仍极具挑战性, 若能以声学超材料攻克, 将对科技发展产生深远影响. 该挑战同样存在于对水中低频声波的调控.

沈平 香港科技大学荣休教授和香港科技大学高等研究院资深成员. 研究领域包括声学超材料、纳米碳结构、电流变液体、流固界面现象、等效介质理论等.

人们常用“声学超材料”在学术刊物、专利及研究提案等标题中出现的频率来判断该领域兴衰. 但实则不然: 相关术语消失于公共视野, 诚然可能预示着该研究领域的式微和消亡; 但也可能标志着该领域走向了最终的商业化成功. 20多年前, “纳米技术”“纳米尺度”“纳米科学”曾是热门的科研主题, 相关字眼频繁地出现在科研论文和研究提案的标题中. 然而, 如今纳米科学的研究已经趋于纯熟, 几乎所有前沿科技都能做到纳米尺度, 相关术语也就鲜少出现在学术研究中了. 纳米科学不再是一个“热门”的研究探索领域, 它已然转而成众多新物理现象、效应及商业化器件的基础. 这些衍生出来的新现象、新效应及商业化器件成了人们关注的新焦点, 无疑标志着纳米技术的研究探索已大获成功. 我们对声学超材料的未来展望亦是如此.

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推荐阅读文献

1 Krushynska A O, Torrent D, Aragón A M, et al. Emerging topics in nanophononics and elastic, acoustic, and mechanical metamaterials: An overview. Nanophotonics, 2023, 12: 659–686

2 Dong E, Cao P, Zhang J, et al. Underwater acoustic metamaterials. Natl Sci Rev, 2023, 10: nwac246

Summary for “声学超材料: 展望未来”

Acoustic metamaterials: outlook for the future

Ping Sheng

Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Hong Kong 999077, China
E-mail: sheng@ust.hk

It has been almost a quarter of a century since the beginning of acoustic metamaterials. During that period, acoustic metamaterials have developed from a scientific curiosity to become an active, diverse, and robust field, encompassing multiple research directions and involving practitioners from almost all disciplines. It is now a legitimate question to ask: What will all these activities lead to? While predicting the future is always risky, the developmental trajectories of some past scientific fields can serve as a guide for looking ahead.

Let us trace the development of semiconductors and liquid crystals, as the two materials have led to inventions that have had profound scientific and technological consequences. For semiconductors, the initial discovery of using dopants to locally alter their electrical characteristics led to the invention of the solid-state transistor. This crossover from material physics to technological breakthrough was instrumental in the subsequent developments, not only in technological advances in micro- and nanoscale devices, but also in the initiation of mesoscopic physics, as well as a host of other scientific areas. For liquid crystals, the same crossover from being a curious new state of matter characterized by not only positional order, but also orientational order, to the technological realization of displays through the electrical manipulation of the interaction between light and orientational order, has had a similar effect in opening up subsequent developments in displays, as well as serving as one of the two paradigms for soft matter physics (the other one being polymers).

A common element in the above two examples is the commercialization of their broad application potential. The initial excitement surrounding the discoveries of new physical phenomena inevitably led to their eventual engineering realization as low-cost products that can either provide solutions to problems that were difficult for traditional means, or create new consumer demands through new product capabilities. The commercialization step is important in providing the funds, directly or indirectly, and motivation for further R&D activities. In contrast, there were other scientific discoveries that generated excitement and research publication opportunities for a period of time, but in the absence of finding useful commercial applications, they can gradually fade with diminishing R&D activities.

For acoustic metamaterials, characterized by the synergistic interaction between wave physics and the infinite possibilities of geometric structures for defined wave functionalities, the field is now in the initial stage of commercialization for some of the functionalities, e.g., acoustic absorption, with others in the various developmental stages that may offer capabilities not attainable by traditional means. Here I wish to mention three areas: Nanoscale phononics, underwater acoustics, and sub-100 Hz acoustic wave manipulations with thin samples. This remains a challenging area that, if realized by acoustic metamaterials, could have broad implications for both scientific and technological developments.

Counting the number of appearances of “acoustic metamaterials” in the titles of publications, patents, and research proposals may often be regarded as a reliable way to judge the rise or decline of this area. However, contrary to this popular view, the disappearance of such terms from public view, while it may surely signal the “demise” of the research area, may also signal its ultimate success. This fact can be simply illustrated by the following example. More than 20 years ago, “nanotechnology” or “nanoscience” constituted a hot area of scientific and technological pursuit. Many research proposals were written with titles that contained such terms. However, such terms no longer appear to be a topic for research pursuit because nanoscale has now diffused into almost every scientific or technological endeavour. It is no longer a “hot” area, so to speak. Instead, it serves as the basic foundation for many of the new physical phenomena, effects, and commercialized devices. The focus is now on these topics, and the initial pursuit of nanotechnology has attained its ultimate success. The same could be the outlook for acoustic metamaterials.

acoustic metamaterials, sound, wave functional materials, classical wave

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