基于超材料的雷达吸波材料研究进展

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摘要 雷达吸波材料能够有效地抑制透射波和反射波，因而被广泛应用于隐身、电磁屏蔽和兼容以及无线通信等领域。受制于材料的电磁频散特性，传统吸波材料的宽带低频吸波性能难以进一步提高。近年来，随着超材料结构设计的不断发展，基于超材料构架设计实现的宽带电磁吸波，由于具有更加灵活的电磁调控能力，因而在其电磁性能提升方面具有更大拓展空间。围绕雷达吸波超材料的最新研究进展，结合电磁吸波超材料的发展背景、设计原理和性能表征方面的内容，着重介绍了基于多谐振叠加吸波结构、超材料与传统材料复合吸波结构、三维阵列吸波结构以及人工表面等离激元吸波结构设计的宽带雷达吸波超材料，并对于未来雷达吸波超材料的发展趋势做进一步展望。

关键词 超材料;雷达吸波材料;宽带

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Research Progresses in Radar Absorbing Materials Based on Meta-Material

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Abstract: Radar absorbing materials (RAM) can effectively inhabit the transmitted waves and the reflected waves widely applied in the field of stealth technology, electromagnetic shielding and compatibility, as well as wireless communications. Suffering from frequency dispersion of electromagnetic parameters, the traditional EAMs still be up against a challenge in further improvement of broadband absorption in the low frequency. Recently, with the development of meta-material design, the achievement of broadband absorption based on meta-material configurations exhibits more performance improvement due to its flexible capability of electromagnetic manipulation. The paper centers on the research progresses in radar absorbing materials based on meta-material structure with the aid of development background, design principles and property characteristic. Specifically, the broadband radar absorbing meta-materials are in detail introduced based on the multi-resonance-integrated absorbing structure, meta-material absorbing structure combined with traditional material, three-dimensional array absorbing structure, as well as spoof surface plasmon polaritons absorbing structure. Furthermore, the paper looks forward to the future of the broadband radar

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absorbing meta-material.
Key words: meta-material; radar absorbing material; broadband

在 20 世纪初的几场局部性战争中,以隐身技术为代表的高新装备在敌我较量中优势明显,成为现代信息化战争中各国竞相争抢的技术高地。隐身技术是指能够有效控制或抑制目标的雷达特征信号使其探测距离与精度下降,从而降低目标被发现、识别、追踪以及摧毁的概率,这对提高武器装备生存力和作战效能具有深远的意义[1-2]。目前,有效的隐身技术方案主要是外形结构隐身和雷达吸波材料隐身。外形结构隐身虽然可以有效地缩减了飞行器的雷达散射截面,但在一定程度上会影响飞行器的气动性能,并且隐身效果具有方向性的限制。而雷达吸波材料受外形结构的约束相对较少,并具有全方位的隐身性能,已逐渐成为电磁隐身技术领域重点研究的对象。与此同时,随着现代电子技术的飞速发展,以电磁波为信息载体的电子设备越来越普及,正悄无声息地改变着人类的生活,其带来的无线信号干扰、信息安全隐患、电磁辐射污染等也同时影响着人们的日常生活和身体健康。减弱或屏蔽电磁辐射的方法有很多,雷达吸波材料便是其中一种有效而又简单的实现途径,其在军用和民用领域都具有广泛的应用价值,成为材料领域研究的热点。对于在工程中应用的吸波材料,由于受应用领域和周围环境的制约,材料的性能指标各不相同。总体来说,研究者们定义的最理想的雷达吸波材料应该具备“厚度薄、质量轻、工作频带宽、吸波能力强”的特点。

传统吸波材料通常由基体材料和吸收剂两部分组成,其吸收性能主要取决于吸收剂的电磁参数及频散特性。研究者先后发展了包括导电高聚物、碳纤维、铁氧体、石墨烯、磁性金属微粉等[3-7]多种材料为吸收剂的复合吸波材料。其中,磁性吸收剂特别是金属微粉由于具有良好的电磁匹配[8]和较强的磁损耗[9]特性而更有利于实现电磁波的吸收。然而,随着频率的进一步降低,材料的磁损耗无法再提供足够的吸收。而受到磁性共振特性和 Snoek 限制[10],传统吸波材料的低频宽带吸波性能较难获得进一步提高。为了突破传统吸波材料性能的瓶颈,研究者们不断探索新的电磁吸收机制。

近年来,随着人工电磁媒质的迅速发展,基于亚波长结构设计的吸波超材料得到了广泛的关注。相比于传统吸波材料,吸波超材料具有吸收率高、厚度薄、质量轻的特点。通过进一步的优化设计,吸波超材料不但能在宽带吸波性能上有望超越传统材料,还展现出了智能可调、可设计性强等新特性,从而在隐身、传感、检测、天线等方面发挥重要作用。本文重点关注基于超材料设计的雷达吸波材料在宽带电磁吸波性能方面的研究进展,详细介绍了其实现方式和性能特点,并结合研究现状对宽带吸波超材料的发展做简单介绍和进一步展望。

1 吸波超材料

超材料是具有亚波长特性的结构单元按照特定的排布周期构成的人工电磁媒质,其电磁特性在很大程度上依赖于周期单元的结构、尺寸、排布等。通过对上述参数的设计可实现对超材料等效电磁参数的灵活调控,进而实现一系列具有负折射率[11]、负介电常数/磁导率[12-16]、逆多普勒效应[17]的电磁特性。这使得超材料能够被广泛应用于隐身衣[18-24]、超级透镜[25-30]、高方向性天线等领域[31-35]。其中,基于超材料的强损耗特性实现的电磁吸波超材料一直被研究者们广泛关注。

早期关于超材料的研究,人们主要是围绕着具有负折射率特性的左手材料展开[36-37],并且设计了一系列具有奇异电磁特性的功能器件。这些设计共同的特点都是通过尽量降低人工介质的损耗来获得理想的电磁奇异特性。2008 年,波士顿大学的 N. I. Landy 等[38]却反其道而行之,将金属开口电谐振环和金属线阵列结构刻蚀在超薄厚度的 FR4 介质板两侧,通过合理地调节单元尺寸,使得该人工电磁媒质在某一频点处产生较强的电磁谐振。由于谐振的影响,该频点处人工媒质的等效介电常数和等效磁导率相等,入射电磁波进入材料内部被完全损耗掉,从而得到了吸波性能在某一频点处近乎完美的吸波超材料。随着超材料结构设计的不断丰富,研究者们设计了一系列具有单带、双带、三带以及多带特性的吸波超材料[39-48],并且其工作频段能够实现从微波频段向太赫兹、红外乃至可见光频段的拓展,为吸波超材料的研究提供了新的空间。对于微波频段的吸波超材料,宽带电磁吸波有着广泛的应用价值,一直是研究者们重点关注的内容。

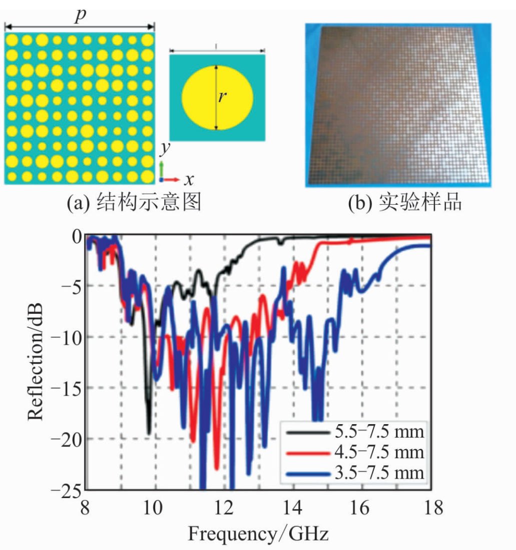
2 雷达吸波超材料的研究进展

基于金属谐振单元、损耗介质和金属背板构成的经典吸波超材料,由于其强电磁谐振特性,在微波频段内表现出明显的窄带吸波效果,将会在一定程度上限制吸波超材料的实际应用。为了进一步拓展吸波超材料的宽带吸波特性,使其吸波带宽能够尽

可能接近于理论极限[49]，研究者们进行了多样化的尝试，其中最典型的是以下几种。

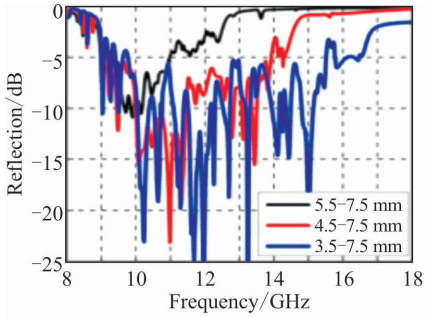
2.1　多谐振叠加吸波结构

研究表明，吸波超材料的谐振频点在一定范围内与其谐振单元的尺寸有着明显的线性关系，因此通过尝试在单位平面内构筑多个不同尺寸的亚波长谐振单元，可以将多个相邻的吸收峰串联在一起，实现具有一定宽带特性的吸波超材料[50-57]。浙江大学何赛灵等[50]将 4 个不同宽度的谐振单元组合在一起，构筑了 4 个相邻的吸收峰，实现了在光频段的宽带吸波。南京理工大学的 Y. Song 等[51]将 3 种不同形状的分形结构单元围绕对称中心进行组合，在微波频段实现了相邻的 3 个吸收峰构筑的宽带吸波。与此同时，面内多谐振单元的排布方式对于宽带吸波性能的影响也是研究者们关注的重点。西北工业大学的赵晓鹏等[52]利用简单的圆形金属谐振单元，通过组合优化单位平面内多谐振单元的数量和排布方式，进一步拓展了其吸波带宽。本课题组利用随机分布的、尺寸连续变化的圆形谐振单元，设计了如图 1 所示的宽带吸波超材料，实现了宽频段内对入射电磁波的高效吸收[53]。此外，为同时兼顾高吸波效率和宽带吸波性能，研究者们尝试将单元尺寸渐变的多谐振单元在垂直空间内进行多层叠加[58-68]。何赛灵等[60-63]提出利用金属贴片与介质基板在垂直空间上间隔叠加构成的金字塔状多层吸波结构，实现了在微波、太赫兹以及红外频段内的宽带吸波特性。武汉理工的官建国等[65]将 3 种不同尺寸的金字塔状多层金属贴片单元在同一平面内进行组合，有效地合并了多阶吸收带，进一步拓宽了其吸波带宽。不过，该类多层结构吸波超材料相较于之前的面内多谐振吸波超材料，其总厚度和质量也明显增加。



(a) 结构示意图　(b) 实验样品

(c) 不同分布区间的随机分布吸波超材料对于垂直入射的TE波的吸波性能



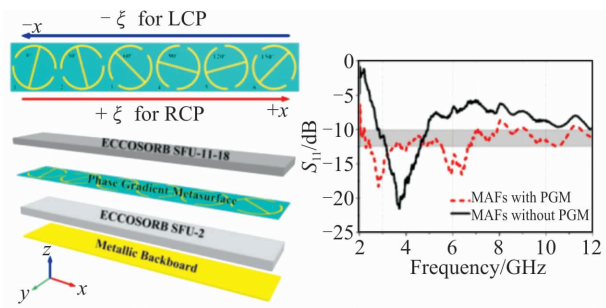
(d) 不同分布区间的随机分布吸波超材料对于垂直入射的TM波的吸波性能

图 1　基于多谐振单元的随机分布构成的宽带吸波超材料

Fig. 1　Broadband MA based on multi-unit resonators in random distribution

2.2　超材料与传统材料复合吸波结构

超材料由于具有灵活可设计的电/磁谐振，其色散特性能够被任意调控。然而，基于金属谐振器，介质基板和金属背板设计的吸波超材料，其强电磁谐振并不利于实现宽带电磁吸波。通过加载传统的损耗元件或吸波媒质，有利于进一步改善等效媒质的阻抗匹配和色散特性，从而达到宽带电磁吸波的目的[71-77]。浙江大学的冉立新等[71]通过在金属谐振单元连接处加载集总电阻，借助损耗调控进一步改善了吸波超材料所激发的电/磁谐振的品质因数，从而获得连续且高效的电磁吸波。本课题组将具有相位梯度特性的超表面置于 2 层磁性吸波材料之间，如图 2 所示，借助超表面对于入射电磁波的异常透射和异常反射特性，能够有效地改变电磁波在磁性吸波材料中的传播路径，进一步拓展了该吸波材料的低频吸波性能[74]。此外，本课题尝试将纯净水与介质基板组合而成的混合基板置于金属谐振器和背板之间，设计了一款基于混合基板的吸波超材料[75]。由于水基板的等效介电常数具有频散特性，使得该吸波超材料能够在微波频段实现高效的宽带吸波性能。由此可见，将超材料结构与传统吸波材料相结合，能够高效地同时兼顾二者的优势，这对于宽带吸波材料综合性能的提升，具有重大的意义。



(a) 结构示意图　(b) 加载与不加载超表面的磁性胶片对于垂直入射电磁波的宽带吸波性能

图 2　磁性胶片加载超表面

Fig. 2　Magnetic absorber loaded with metasurface

2.3 三维阵列吸波结构

由金属谐振器,介质基板和金属背板构成的3层吸波结构,因其厚度远小于波长,可以被近似认为是二维结构的人工电磁媒质。该平面结构的人工电磁媒质,其激发的电磁谐振的模式相对简单,较难在超薄的厚度下获得连续的宽带电磁吸波性能。因此,研究者们尝试将亚波长谐振单元的设计由二维平面向三维空间拓展,设计出一系列非平面结构的三维吸波超材料[76-80]。官建国[78]通过在站立的磁性基板阵列侧面印制周期排布的金属电/磁谐振器,充分利用电/磁谐振以及磁性基板的频散特性,在微波频段更宽的频段内实现了高效的电磁吸波。本课题组尝试将具有较强欧姆损耗的电阻薄膜构成方形晶格阵列,以一定周期置于金属背板上,构成了三维电阻片阵列吸波超材料。如图3所示,该吸波超材料能够在站立的电阻片表面激发多重驻波模式,便于实现连续且高效的宽带电磁吸波[77]。进一步借鉴三维折纸结构,利用电阻薄膜折叠组合成如图4所示的结构单元,并置于金属背板上[78]。该吸波结构不仅具备宽带的电磁吸波特性,同能对大角度入射的TM波仍能实现高效的宽带电磁吸波。因此,基于三维阵列结构的优化设计,将有助于吸波超材料综合性能的提升。

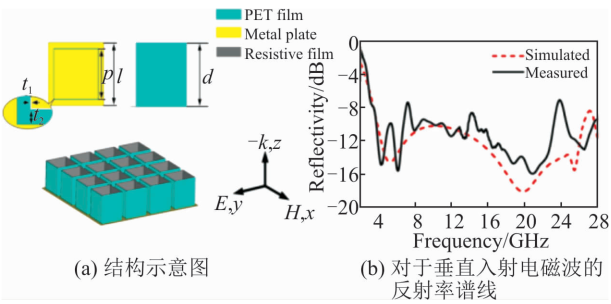


图3 电阻片阵列吸波超材料

Fig. 3 MA based on standing-up resistive patch array

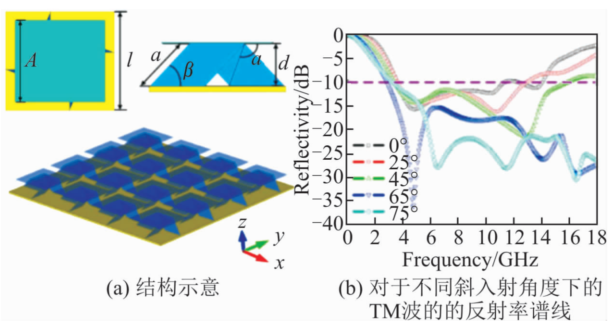


图4 折纸结构吸波超材料

Fig. 4 MA based on standing-up resistive origami structure

2.4 人工表面等离激元吸波结构

人工表面等离激元是金属结构在可见光频段下,所激发的自由电子局域在金属表面传播的一种特有的电磁现象。而在微波频段,基于亚波长金属谐振单元的组合排布,入射电磁波能够被有效的局域在金属-介质面内,并以慢波的形式沿着金属阵列的拓扑方向进行传播[81-82]。此时,若介质基板给予足够的介电损耗,电磁能量能够高效地被该人工表面等离激元结构所吸收。本课题组提出利用多层渐变结构简化成二维平面结构,如图5所示,将长度渐变的金属线阵列印刷于二维介质格栅侧面,借助于所激发的人工表面等离激元,实现高效的宽带电磁吸波[83]。该设计在不影响宽带吸波特性的同时,可以进一步减轻吸波超材料的总质量。与此同时,如图6所示,通过构造弯折的金属线阵列,可进一步合并原本离散的高阶吸收带,实现连续的超宽带电磁吸波[84]。尽管使用多层复合结构能够在更宽的频带范围内实现高效的电磁吸波,然而所设计的吸波超材料的厚度也将不可避免地随之增大。

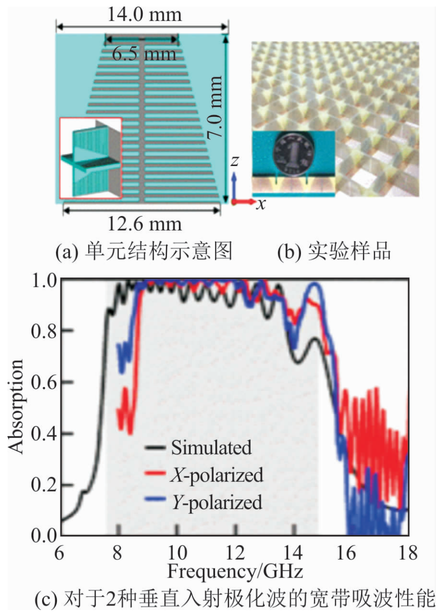
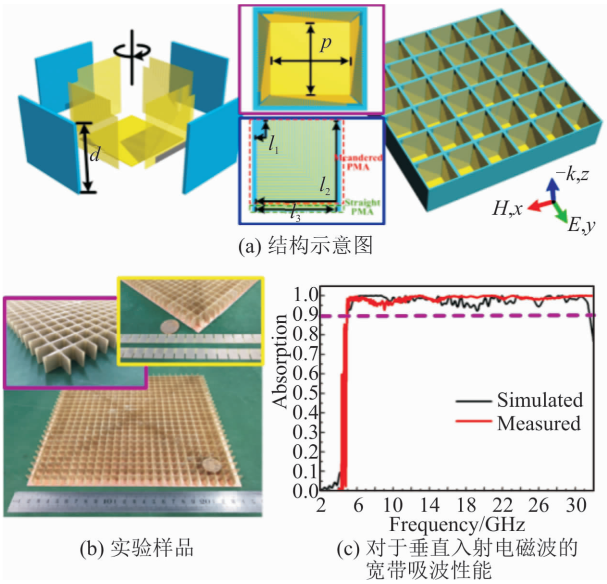


图5 多层金属线等离子结构吸波超材料

Fig. 5 Plasmonic absorbing structure based on multi-layered wires

3 雷达吸波超材料的发展趋势

研究者们仍在努力探索更多新的物理机制和实现方法来追求吸波超材料的宽带吸波性能。与此同时,结合宽带吸波超材料的实际应用背景,基于亚波长结构的灵活调控实现的多功能一体化设计也进一步指明了未来关于宽带吸波超材料研究的发展趋势。



(a) 结构示意图

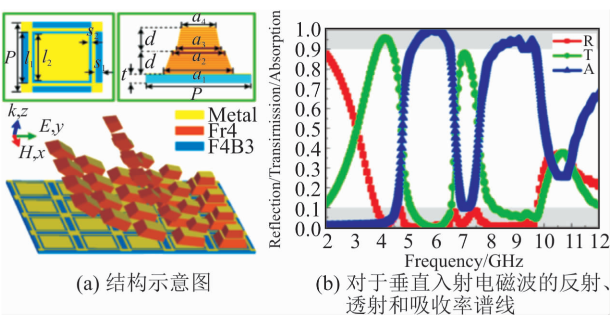
(b) 实验样品　　(c) 对于垂直入射电磁波的宽带吸波性能

图 6　多层弯折线等离子结构吸波超材料

Fig. 6　Plasmonic absorbing structure based on multi-layered meandered wires

3.1　吸波-透波一体化超材料

在追求宽带电磁吸波的同时，如果能够在特定频域内实现高效率的电磁透波，将更有助于吸波超材料在天线罩、电磁屏蔽、探测感知方面的应用。这种吸波-透波一体化的性能特征，需要借助于具有可设计特性的人工电磁媒质去实现[85-88]。南洋理工大学的沈忠翔等[85]通过组合加载集总电阻的金属谐振结构和频率选择表面，设计得到了一款可在宽吸波频带中间处实现高透波特性的人工电磁媒质。与此同时，为了进一步缩减吸波频带与透波频带之间的过度带宽，实现类似于“窗口效应”的吸波-透波一体化性能，本课题组提出利用多层叠加的吸波超材料结合底层的频率选择表面，设计了一款非平面的吸透一体化超材料[88]。如图 7 所示，2 款尺寸不同的多层金字塔超材料吸波体在垂直方向上叠加，获得了 2 段高效的吸波带。而底层的频选表面结构，可同时实现 2 个吸波带之间以及吸波带以外的高效电磁透波。这种更加灵活的宽带电磁吸波和高效电磁透波一体化的调控，进一步丰富了宽带电磁吸波超材料的应用价值。



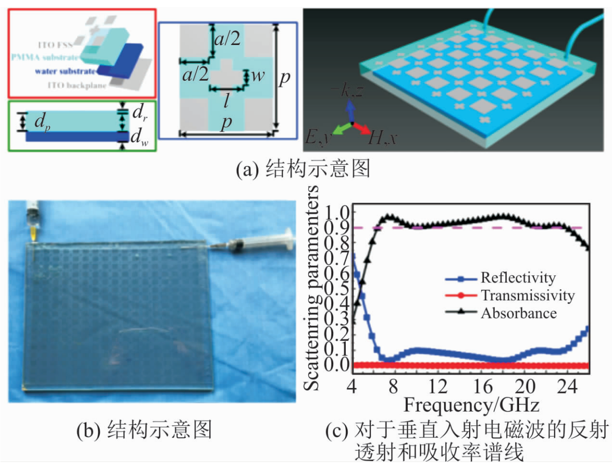
(a) 结构示意图　　(b) 对于垂直入射电磁波的反射、透射和吸收率谱线

图 7　吸波-透波一体化超材料

Fig. 7　Absorption-transmission-integrated metamaterial

3.2　多频谱兼容的吸波超材料

关于宽带雷达吸波材料的应用研究，在微波频段、红外频段、太赫兹频段以及可见光频段已经取得了较多的技术成果。然而，能够同时兼顾多个频谱的应用需求的超材料研究才刚刚拉开序幕[89-94]。浙江大学的马云贵等[89]通过在加载集总电阻的宽带电磁吸波超材料表面覆盖一层红外屏蔽层，在不影响吸波超材料在微波频段的宽带电磁吸波性能的同时，还进一步降低了材料在红外频段的发射率。东南大学的崔铁军等[92]利用透明 ITO 导电薄膜结合有机玻璃实现了一款对于可见光几乎透明，同时在微波频段具有宽带吸波性能的吸波超材料。本课题组利用纯净水结合透明的 ITO 导电薄膜，设计了一款透明的水基体的宽带吸波超材料[93]。由于纯净水的频散特性和 ITO 导电薄膜的强欧姆损耗，该吸波材料能够在微波频段实现高效且宽带的电磁吸波。同时，由于该装置中液态水的可循环特性，具有较大比热容的水基体能够有效的控制该吸波超材料的红外热辐射，实现了微波、红外和可见光多频谱兼容的吸波超材料。



(a) 结构示意图

(b) 结构示意图　　(c) 对于垂直入射电磁波的反射、透射和吸收率谱线

图 8　透明的水基体宽带吸波材料

Fig. 8　Transparent water-substrate MA

3.3　多物理场兼容的吸波超材料

利用人工媒质设计实现入射电磁波宽带强吸收的同时，研究者们还希望所设计的人工电磁媒质同时具备其他物理特性[95-96]。图卢兹大学的 J. Morlier 等[91]尝试在蜂窝结构的单元晶格内填充磁性吸波材料，使得所设计的吸波超材料在微波频段实现宽带电磁吸波的同时，还具有较强的力学稳定性能。东南大学的崔铁军等[92]在介质格栅上下 2 层粘连 ITO 导电薄膜，不仅实现了对入射电磁波的宽带强吸收，同时该结构也被证实具有较强的声学隔离特性，实现了电磁吸波和声学隔离一体化的设计。可以说，将吸波超材料与其他物理场特性的有机结合，

能够更加全面地分析所设计的吸波超材料的综合性能指标,更加有利于吸波超材料的实际利用。

4 结语

总之,雷达吸波材料由于其在军事和民用方面都有着十分广泛的应用前景,长期以来受到世界各国研究者的关注。随着材料制备水平以及微观结构表征能力的不断提高,传统材料吸波性能的提升难度越来越大。超材料由于其不同寻常的电磁响应特性得到了快速的发展,成为当前国际学术界的研究热点和前沿。它的出现使得人们能够从宏观尺度层面上设计和控制材料的电磁响应特性,极大地拓展了雷达吸波材料的发展空间。然而,作为一门新兴的学科分支,电磁吸波超材料在实际的应用研究领域中仍处于前期的探索阶段。近年来,关于宽带电磁吸波超材料的研究不断从二维平面结构向更为复杂的三维结构拓展。其性能追求,也由过去单一地关注"薄、轻、宽、强"的指标,发展到现在的多频谱、多物理场结合的综合指标。相信随着研究者们的不断创新与探索,吸波超材料将获得更加广泛的应用价值。

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