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用钕铁硼(NdFeB)永磁材料实现磁斗篷*

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固有磁化强度方向与外磁场方向相反的钕铁硼 (NdFeB) 空心圆柱和固有磁化强度方向与外磁场方向相同的钕铁硼铬 (NdFeCrB) 空心圆柱镶嵌在一起, 组成一个磁化强度方向相反的双层磁环. 利用柱坐标系中磁标势的公式及本构关系, 推导了均匀外磁场在双层空心圆柱永磁体内外的磁场强度, 得到了半径比率与外加磁场、相对磁导率及磁化强度的关系. 计算结果表明, 当施加均匀外磁场时, 双层空心圆柱 NdFeB 永磁体可以屏蔽静磁场从而实现磁斗篷.

关键词: 静磁场隐身, 斗篷, 永磁材料

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1 引 言

自 2006 年 Pendry 和 Leonhardt 等[1,2] 提出利用坐标变换来设计材料的特性, 使电磁波沿着特定的路线传播从而实现隐身以来, 基于变换光学理论的隐身斗篷得到了科学界的广泛关注和研究. 近几年来, 电磁斗篷[3,4]、声斗篷[5,6]、物质波斗篷[7]、热斗篷[8]、质量扩散斗篷[9]、电斗篷[10,11]和磁斗篷[12,13] 等各种各样的斗篷已在理论设计和实验研究中被相继提出. 其中, 电磁斗篷、电斗篷或磁斗篷的实现是最引人关注的[3,14−22]. Schurig 等[3] 用具有人工结构的超材料实验验证了电磁波斗篷, 该斗篷通过降低散射进而减小隐藏对象的身影, 让斗篷和隐藏对象在自由空间变得相似, 从而实现隐身. Yang 等[17] 将导电材料类比为电阻网络, 设计了一个直流电隐身斗篷, 该直流电斗篷能够顺利引导隐形周边区域的电流, 并保持对电流的扰动仅限于斗篷区域内部, 而斗篷区域之外的电流线恢复到原来的方向, 好像什么也没有发生. 2012 年, Gömöry 等[14] 设计了抗磁体磁斗篷, 该斗篷既可以使斗篷中的任何磁场都不会传播到斗篷范围之外, 又可以使斗篷和斗篷覆盖的区域不会被外磁场探测到, 但是这种斗篷设计结构比较复杂. 随后, Prat-Camps 等[23] 提出了一种简单的双层结构来实现磁斗篷, 该斗篷内层由高温超导带制成, 外部由数匝厚铁镍铬 (FeNiCr) 工业合金片铁磁层构成. 然而, 该磁斗篷使用的是超导材料, 而超导材料的使用条件较苛刻, 成本高昂. 本文利用 NdFeB 永磁材料设计了一个双层空心圆柱斗篷, 推导了结构参数和材料参数之间的关系, 理论计算结果表明该斗篷可以屏蔽外加的静磁场, 从而实现静磁斗篷.

2 静磁场屏蔽原理

静磁屏蔽的原理如图 1 所示. 当圆柱的相对磁导率 $\mu_c = 1$ 与周围的相对磁导率 $\mu_s = 1$ 相同, 固有磁化强度 $\boldsymbol{M}$ 为零时, 磁场线在圆柱内外是平行的

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匀强磁场, 圆柱对外磁场没有任何影响, 如图1 (a) 所示. 当圆柱固有磁化强度方向与外磁场相反时, 磁场线将受到圆柱的排斥, 如图1 (b) 所示. 而当圆柱固有磁化强度方向与外磁场相同时, 磁场线将受到圆柱的吸引, 如图1 (c) 所示.

图1表明: 与外磁场同方向的固有磁化强度吸引磁场线, 而反方向的固有磁化强度排斥磁场线, 因而圆柱固有磁化强度方向与外磁场相同或相反时都会扰乱磁场. 而以特定半径比构成的固有磁化强度方向相反的双层圆柱结构则可调整固有磁化强度使之完全不扰乱外磁场. 利用这一原理, 设计了双层空心圆柱静磁斗篷.

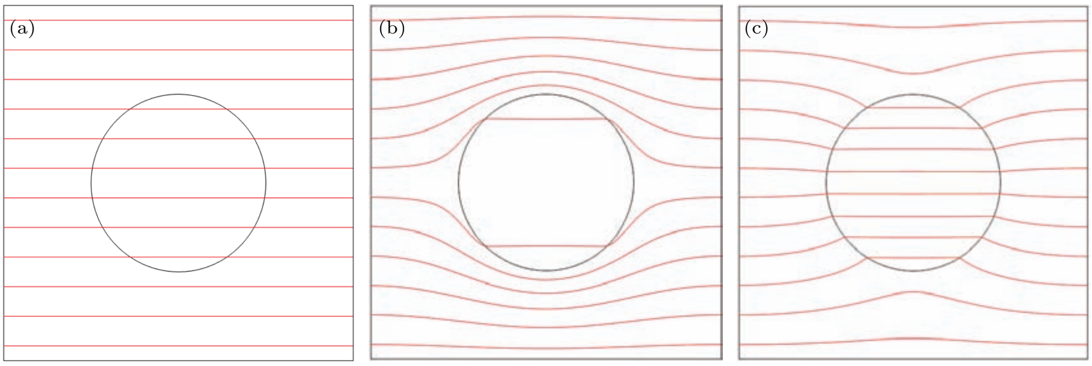

图1 静磁场屏蔽原理. 圆柱相对磁导率 ($\mu_c = 1$) 与周围的相对磁导率 ($\mu_s = 1$) 相等 (a) 圆柱固有磁化强度 $M = 0$, 圆柱对外磁场没有任何影响; (b) 圆柱固有磁化强度大小 $M = 15000$ A/m, 方向与外磁场相反, 磁场线将受到圆柱的排斥; (c) 圆柱固有磁化强度大小 $M = 15000$ A/m, 方向与外磁场相同, 磁场线将受到圆柱的吸引

Fig. 1. Principle of magneto-static shielding. The relative permeability of the cylinder ($\mu_c = 1$) is equal to that of the surrounding ($\mu_s = 1$): (a) The cylinder has no effect on the applied magnetic field when the intrinsic magnetization intensity of the cylinder M is zero; (b) when the direction of the intrinsic magnetization intensity ($M = 15000$ A/m) is opposite to that of the applied magnetic field, the magnetic field lines are repelled by the cylinder; (c) when the direction of the intrinsic magnetization intensity ($M = 15000$ A/m) is the same as that of the applied magnetic field, the magnetic field lines are attracted by the cylinder.

3 双层空心圆柱静磁斗篷

双层空心圆柱静磁斗篷的结构如图2所示, 内层圆柱由NdFeB材料制成, 内外半径分别为c和b; 外层圆柱由掺杂铬的NdFeCrB材料制成, 内外半径分别为b和a. 双层空心圆柱的相对磁导率分别为μ_2和μ_3, 固有磁化强度分别为$\boldsymbol{M}_2$和$\boldsymbol{M}_3$, 磁化强度的方向如图2 所示.

当施加一匀强磁场$\boldsymbol{H}_0$时, 四个区域的磁标势在柱坐标系(r, θ, z)中可表示为[14]

$$\phi_{\mathrm{m}1} = \left(-\boldsymbol{H}_0 r + \frac{A}{r}\right)\cos\theta, \tag{1}$$

$$\phi_{\mathrm{m}2} = \left(Br + \frac{C}{r}\right)\cos\theta, \tag{2}$$

$$\phi_{\mathrm{m}3} = \left(Dr + \frac{E}{r}\right)\cos\theta, \tag{3}$$

$$\phi_{\mathrm{m}4} = Fr\cos\theta, \tag{4}$$

式中$\phi_{\mathrm{m}1}$, $\phi_{\mathrm{m}2}$, $\phi_{\mathrm{m}3}$, $\phi_{\mathrm{m}4}$分别是四个区域的磁标势, A, B, C, D, E, F为未知系数.

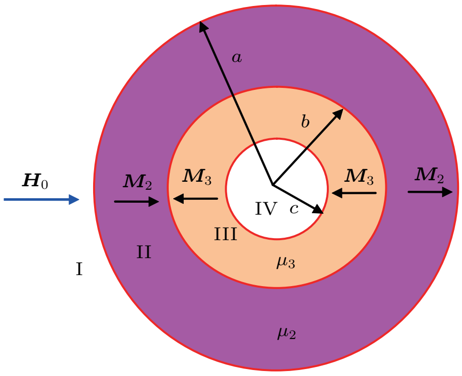

图2 双层圆柱磁斗篷, 区域I和IV都是真空, 区域II是由NdFeCrB永磁材料制成的空心磁环, 区域III是由NdFeB永磁材料制成的空心磁环

Fig. 2. The bi-layer cylinder magneto-static cloak, regions I and IV are both vacuum, region II is a magnetic ring made of NdFeCrB permanent magnetic material, region III is a magnetic ring made of NdFeB permanent magnetic material.

在本研究中, 假设内外层材料均被均匀磁化. 当存在外磁场$\boldsymbol{H}$时, 磁性材料的总磁化强度$\boldsymbol{M}_{\mathrm{total}} = \boldsymbol{M}' + \boldsymbol{M} = \chi_{\mathrm{m}}\boldsymbol{H} + \boldsymbol{M}$, 故有

$$\begin{aligned}\boldsymbol{B} &= \mu_0(\boldsymbol{H}+\boldsymbol{M}_{\text{total}}) = \mu_0(\boldsymbol{H}+\chi_{\text{m}}\boldsymbol{H}+\boldsymbol{M})\\ &= \mu\mu_0\boldsymbol{H}+\mu_0\boldsymbol{M},\end{aligned}\tag{5}$$

式中μ_0是真空的磁导率, $\boldsymbol{B}$是磁感应强度, $\boldsymbol{M}$是永磁材料的固有磁化强度, $\boldsymbol{M}'$是由外磁场引起的磁化强度, χ_{m}是磁极化率. 磁场强度和磁标势之间的关系为

$$\boldsymbol{H} = -\nabla\phi_{\text{m}},\tag{6}$$

式中$\boldsymbol{H}$是磁场强度, $\nabla = \dfrac{\partial}{\partial r}\boldsymbol{e}_r + \dfrac{1}{r}\dfrac{\partial}{\partial\theta}\boldsymbol{e}_\theta + \dfrac{\partial}{\partial z}\boldsymbol{e}_z$, 故四个区域的磁场强度可表示为

$$\begin{aligned}&\boldsymbol{H}_1 = -\nabla\phi_{\text{m}1}\\ &= \left(H_0+\frac{A}{r^2}\right)\cos\theta\boldsymbol{e}_r + \left(-H_0+\frac{A}{r^2}\right)\sin\theta\boldsymbol{e}_\theta,\end{aligned}\tag{7}$$

$$\begin{aligned}&\boldsymbol{H}_2 = -\nabla\phi_{\text{m}2}\\ &= \left(-B+\frac{C}{r^2}\right)\cos\theta\boldsymbol{e}_r + \left(B+\frac{C}{r^2}\right)\sin\theta\boldsymbol{e}_\theta,\end{aligned}\tag{8}$$

$$\begin{aligned}&\boldsymbol{H}_3 = -\nabla\phi_{\text{m}3}\\ &= \left(-D+\frac{E}{r^2}\right)\cos\theta\boldsymbol{e}_r + \left(D+\frac{E}{r^2}\right)\sin\theta\boldsymbol{e}_\theta,\end{aligned}\tag{9}$$

$$\boldsymbol{H}_4 = -\nabla\phi_{\text{m}4} = -F\cos\theta\boldsymbol{e}_r + F\sin\theta\boldsymbol{e}_\theta,\tag{10}$$

式中$\boldsymbol{e}_r$是法向单位矢量, $\boldsymbol{e}_\theta$是切向单位矢量.

利用方程(1)—(10)和磁场的边界条件(切向的磁场强度或磁标势在界面$r = a$, $r = b$及$r = c$处连续), 可得

$$-H_0+\frac{A}{a^2} = B+\frac{C}{a^2},\tag{11}$$

$$D+\frac{E}{b^2} = B+\frac{C}{b^2},\tag{12}$$

$$D+\frac{E}{c^2} = F,\tag{13}$$

法向的磁感应强度在界面也连续, 即

$$\begin{aligned}&\mu_i\mu_0\frac{\partial\phi_i}{\partial r}+\mu_0M_i\cos\theta\\ &= \mu_{i+1}\mu_0\frac{\partial\phi_{i+1}}{\partial r}+\mu_0M_{i+1}\cos\theta\end{aligned}$$

$(i = 1, 2)$, 故有

$$\begin{aligned}&\mu_0\left(H_0+\frac{A}{a^2}\right)\\ &= \mu_2\mu_0\left(-B+\frac{C}{a^2}\right)+\mu_0M_2,\end{aligned}\tag{14}$$

$$\begin{aligned}&\mu_3\mu_0\left(-D+\frac{E}{b^2}\right)-\mu_0M_3\\ &= \mu_2\mu_0\left(-B+\frac{C}{b^2}\right)+\mu_0M_2,\end{aligned}\tag{15}$$

$$\mu_3\mu_0\left(-D+\frac{E}{c^2}\right)-\mu_0M_3 = -\mu_0F.\tag{16}$$

由方程(7)和(10)可知, 当$A = 0$和$F = 0$时, 区域I的磁场依然为$\boldsymbol{H}_0$, 而区域IV的磁场则消失, 这就说明此时双层空心圆柱可以屏蔽外加的静磁场, 实现静磁斗篷.

再解方程(11)—(16), 可得

$$\frac{b^2}{c^2} = \frac{M_3(\mu_2-\mu_3)}{M_3(\mu_2-\mu_3)-2\mu_3(\mu_2+1)H_0},\tag{17}$$

$$\begin{aligned}\frac{a^2}{c^2} &= \frac{M_2(\mu_2-\mu_3)+H_0(\mu_2+1)(\mu_2+\mu_3)}{M_2(\mu_2-\mu_3)+H_0(\mu_2-\mu_3)(\mu_2-1)}\\ &\times\frac{M_3(\mu_2-\mu_3)}{M_3(\mu_2-\mu_3)-2\mu_3(\mu_2+1)H_0},\end{aligned}\tag{18}$$

$$\frac{a^2}{b^2} = \frac{M_2(\mu_2-\mu_3)+H_0(\mu_2+1)(\mu_2+\mu_3)}{M_2(\mu_2-\mu_3)+H_0(\mu_2-\mu_3)(\mu_2-1)}.\tag{19}$$

假设给定内层圆柱的相对磁导率$\mu_3 \approx 1.00$, 固有磁化强度大小$M_3 = 9.34\times10^6$ A/m; 外层圆柱的相对磁导率$\mu_2 = 1.005$, 固有磁化强度大小$M_2 = 9.91\times10^6$ A/m. 由方程(17)可得$b/c = \sqrt{46701/(46701-4.01H_0)}$, 又因为$b/c > 0$, 所以$H_0 < 11646$ A/m, 这就意味着该磁斗篷屏蔽的磁场小于11646 A/m. 另外, 如果对NdFeB进行不同的掺杂, 则可以得到不同的相对磁导率μ_2和固有磁化强度大小M_2, 这样就可以屏蔽不同的磁场.

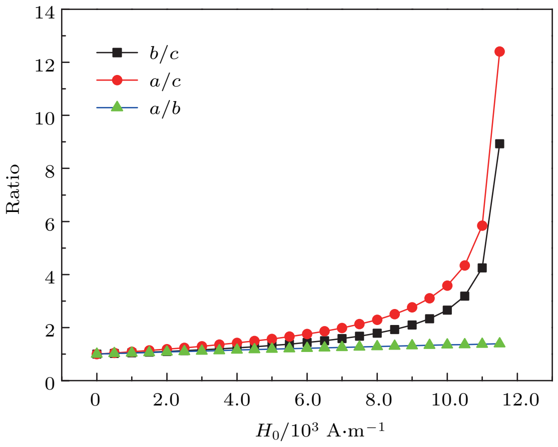

图3 半径比$(a/c, b/c, a/b)$与所加磁场H_0的关系 其他参数为$\mu_2 = 1.005$, $\mu_3 = 1.00$, $M_2 = 9.91\times10^6$ A/m, $M_3 = 9.34\times10^6$ A/m

Fig. 3. The relation between the radius ratios $(a/c, b/c, a/b)$ and the applied magnetic field H_0. The parameters are $\mu_2 = 1.005$, $\mu_3 = 1.00$, $M_2 = 9.91\times10^6$ A/m, $M_3 = 9.34\times10^6$ A/m.

给定双层空心圆柱磁斗篷内层圆柱的相对磁导率$\mu_3 \approx 1.00$, 固有磁化强度大小$M_3 = 9.34 \times 10^6$ A/m, 外层圆柱的相对磁导率$\mu_2 = 1.005$, 固有磁化强度大小$M_2 = 9.91 \times 10^6$ A/m. 根据方程(17)—(19), 可以计算得到半径比a/c, b/c, a/b与所加磁场强度大小H_0之间的关系曲线, 如图3所示.

从图3的关系曲线可以发现, 当半径比$a/c = 3.57947$, $b/c = 2.65971$时, 双层空心圆柱材料可以对磁场强度大小为$H_0 = 10000$ A/m的磁场实现静磁斗篷; 当半径比$a/c = 1.85916$, $b/c = 1.50434$时, 又可以对磁场强度大小为$H_0 = 6500$ A/m的磁场实现静磁斗篷. 半径比与磁场强度之间的关系曲线表明, 通过改变双层圆柱的半径比就可以得到想要的静磁斗篷.

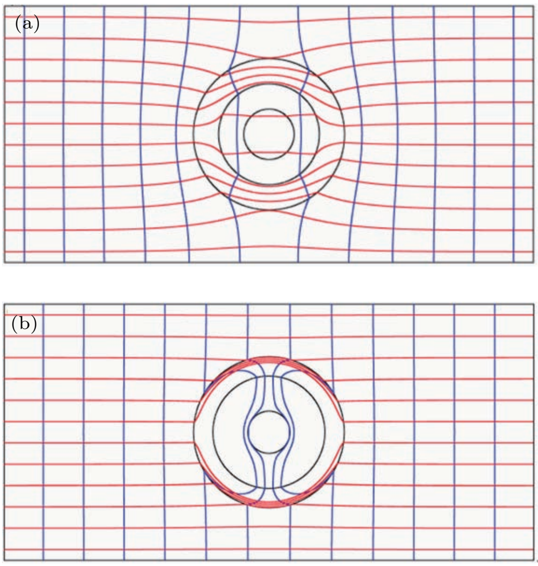

图4 (网刊彩色)双层空心圆柱场分布 (a)非磁斗篷示意图; (b)磁斗篷示意图. 红色为磁场线, 蓝色为等位线

Fig. 4. (color online) The field distribution of the bi-layer cylinder: (a) The bi-layer magnetic non-cloak; (b) the bi-layer magnetic cloak. The red lines are magnetic field lines and the blue lines are equipotential lines.

若其他参数均不变, $H_0 = 10000$ A/m时, 选取半径比$a/c = 3.00$, $b/c = 2.00$, 因该组数据不满足半径比与磁场强度之间的关系曲线, 此时应为非静磁斗篷, 如图4(a)所示, 其中红色为磁场线, 蓝色为等位线, 该图表明当匀强磁场加入到双层空心圆柱形永磁材料中时, 外层圆柱外为非匀强磁场, 并且在内层圆柱内有磁场分布, 无法实现磁斗篷. 图4(b)为各参数间满足(17)—(19)式时的静磁斗篷示意图, 其中红色为磁场线, 蓝色为等位线, 该图表明当匀强磁场加入到双层空心圆柱形永磁材料中时, 永磁材料外仍为匀强磁场, 但进入永磁材料后磁场线发生弯曲, 沿着圆柱环绕并穿出该材料, 在内层圆柱内没有磁场分布, 且磁场线穿出永磁材料后仍然为平行线, 与未经过双层磁环前一样, 从而实现磁斗篷. 通过以上分析不难发现, 只要相对磁导率、固有磁化强度、外加磁场、半径比满足方程(17)—(19), 就可以实现磁斗篷. 根据这种方法, 如果实际测得的相对磁导率并非文章所给的值, 则可以通过调整其他参数, 使各参数间满足方程(17)—(19), 依然可以实现磁斗篷.

4 结 论

利用永磁材料设计了一个双层空心圆柱斗篷, 根据磁场的边界条件, 得到了各区域的磁标势和磁场强度. 研究结果表明, 通过调节双层永磁材料圆柱的结构尺寸、相对磁导率和固有磁化强度, 可以完美实现外加静磁场的磁斗篷. 另外, 该磁斗篷所用的NdFeB永磁材料是一种很常见、很容易获得的材料, 为其设计在实验上实现并应用提供了极大的便利.

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Magnetic cloak made of NdFeB permanent magnetic material[*]

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Abstract

In the past few years, the concept of an electromagnetic invisibility cloak has received much attention. Based on the pioneering theoretical work, invisibility cloaks have been greatly developed. Inspired by those theoretical researches, varieties of electromagnetic cloaks, acoustic cloaks, matter wave cloaks, mass diffusion cloaks, heat cloaks, magnetic cloaks, dc magnetic cloaks and electrostatic cloaks have been designed theoretically and demonstrated experimentally.

The first experimentally demonstrated invisible cloak is made of metamaterial with simplified material parameters. The simplified cloak inherits some properties of the ideal cloak, but finite scattering exists. It is difficult to develop a perfectly invisible electromagnetic cloak having homogeneous and anisotropic components by using the natural materials. In this work, a bi-layer magnetic cloak made of neodymium iron boron (NdFeB) permanent magnetic material is designed. When the direction of the intrinsic magnetization intensity of the material is opposite to that of the applied magnetic field, the magnetic field lines will be repelled. When the direction of the intrinsic magnetization intensity is the same as the direction of applied magnetic field, the magnetic field lines will be attracted. With those properties, the two magnetic rings are designed, one is made of NdFeB, and the other is made of neodymium iron chromium boron (NdFeCrB). The direction of the intrinsic magnetization intensity is opposite or parallel to the applied magnetic field. The two magnetic rings nest a bi-layer magnetic ring. When a uniform magnetic field is applied, by using the formulas of the magnetic scalar potential in a cylindrical coordinate system and the constitute relations of magnetic rings, the distribution of magnetic field and scalar potential within the bi-layer concentric cylindrical permanent magnetic material are deduced. Based on theory as demonstrated, the bi-layer permanent magnetic material cylinder can cloak a magneto-static field. Under the conditions of the magnetic cloak with the specific relative permeability and the intrinsic magnetization intensity, the relation between the radius ratio and the applied magnetic field is obtained. The calculation results show that when the radius ratio and the applied magnetic field satisfy this relationship, the bi-layer permanent magnetic material cylinder can cloak the magneto-static field. The magnetic field distributions of both the magnetic non-cloak and magnetic cloak are simulated to show the effectiveness of the proposed theory.

In summary, the results show that the cloak performance is influenced not only by the size parameters of the permanent magnetic material cylinder but also the relative permeability, the intrinsic magnetization intensity, and the applied magnetic field. The NdFeB permanent magnetic material used in the magnetic cloak is very common and can be easily obtained, which gives more convenience for the design and application of the magnetic cloak.

Keywords: magneto-static shielding, cloak, permanent magnetic material

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