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Superposition of DC magnetic fields by cascading multiple magnets in magnetic loops

Fei Sun[1] and Sailing He[1,2,a]
[1]*Centre for Optical and Electromagnetic Research, Zhejiang Provincial Key Laboratory for Sensing Technologies, JORCEP, East Building #5, Zijingang Campus, Zhejiang University, Hangzhou 310058, China*
[2]*Department of Electromagnetic Engineering, School of Electrical Engineering, Royal Institute of Technology (KTH), S-100 44 Stockholm, Sweden*

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A novel method that can effectively collect the DC magnetic field produced by multiple separated magnets is proposed. With the proposed idea of a magnetic loop, the DC magnetic field produced by these separated magnets can be effectively superimposed together. The separated magnets can be cascaded in series or in parallel. A novel nested magnetic loop is also proposed to achieve a higher DC magnetic field in the common air region without increasing the DC magnetic field in each magnetic loop. The magnetic loop can be made by a magnetic hose, which is designed by transformation optics and can be realized by the combination of super-conductors and ferromagnetic materials. [http://dx.doi.org/10.1063/1.4931949]

I. INTRODUCTION

The DC magnetic field produced by a single magnet diverges very quickly in the free space and is limited by many factors (e.g. the rated current of the coil). One simple way to obtain a higher DC magnetic field is to cascade many magnets together. However, there is no theoretical guide on how to efficiently put multiple magnets together to get an enhanced magnetic field.

Transformation optics (TO) is a novel method that can be utilized to control the DC magnetic field.[1–4] In recent years, many novel devices for DC magnetic fields, such as DC magnetic cloaks,[5,6] concentrators,[7–12] lenses,[13] magnetic hoses,[14,15] and illusion devices for DC magnetic fields[4] have been designed by TO. A magnetic hose (MH) is a special kind of medium that has been designed by TO and experimentally demonstrated by DC metamaterials.[14] By extending a surface in the reference space to a region of space in the real space, we can obtain the MH filled in this region in the real space. Such a special medium is also called the null-space medium,[13,16] optical void,[17] or optic-null medium[18] for the electromagnetic wave case. An MH performs like a special 'waveguide' for DC magnetic fields, transferring the DC magnetic field to an arbitrarily long distance.[14]

Previous studies on the MH are focused on transferring the DC magnetic field to a long distance (without enhancement).[14,15] Some other potential applications of the MH has also been proposed, e.g., increasing the magnetic coupling between nanomagnets,[19] and controlling the quantum systems.[20] However there is no study on collecting DC magnetic field and achieving a higher DC magnetic field in an air region through the magnetic loop composed by the MH. We first propose the idea of effectively collecting DC magnetic fields produced by separated magnets and obtain a higher enhanced DC magnetic field in an air region through magnetic loops in this paper.

In this paper we study how to effectively collect the DC magnetic field produced by many separated magnets together to form an enhanced DC magnetic field that cannot be achieved by a single magnet. More specifically, we use MHs to form a DC magnetic loop and place magnets

[a]Corresponding author: sailing@kth.se

inside of this loop to cascade these magnets together. In this way the energy of these magnets can be effectively utilized. Numerical simulations based on the finite element method (FEM) verify our method (All simulations in this paper use the AC/DC module of COMSOL MULTIPHYSICS software).

II. THE MAGNETIC HOSE

We first summarize the basic concept of an MH that has been designed by TO.[14,15] An MH is a highly anisotropic medium whose permeability is infinitely large along its main axis (the direction that the DC magnetic flux is guided along) $\mu_{\|} \to \infty$, and nearly zero in other directions orthogonal to its main axis $\mu_{\perp} \to 0$. For example, we can express the permeability of an MH whose main axis is in a Cartesian coordinate system as:

$$\mu = \begin{cases} diag(\infty, 0, 0), \text{ the main axis is along } x \text{ direction} \\ diag(0, \infty, 0), \text{ the main axis is along } y \text{ direction} \\ diag(0, 0, \infty), \text{ the main axis is along } z \text{ direction} \end{cases} \tag{1}$$

A previous study has shown that MHs can be approximately realized by the combination of super-conductors (SCs) whose permeabilities are extremely small (due to its nearly perfect diamagnetism and ferromagnetic materials (FMs) whose permeabilities can be very large.[14] The simplest simplified version of MH is a structure with a superconductor shell and a ferromagnetic core, which can still perform approximately like an MH.

If we set a magnet at the bottom of an MH (see Figure 1(a)), the upper part of the magnetic flux distribution of this magnet is shifted to the output surface of the MH. If we just remove the region of the MH and connect together the output surface and input surface of the MH in Figure 1(a), we can obtain almost the same flux distribution in Figure 1(b) (i.e., the MH does not change the field distribution in outside the region of the MH as if the region of the MH does not exist). The MH just performs like a space that does not exist for the DC magnetic field outside the MH. Therefore we can also call the MH the null-space medium.

III. A MAGNETIC LOOP

The basic idea of our method is that we use an MH to form a closed magnetic loop and place some magnets inside this loop. The magnetic flux produced by these separated magnets can be

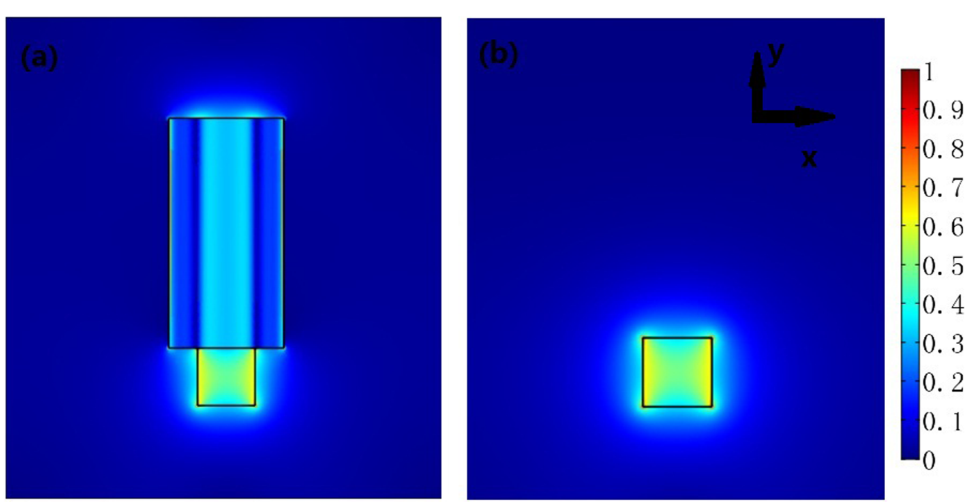

FIG. 1. FEM simulation results: the absolute value of the magnetic flux density distribution for (a) a magnet with a residual induction $B_r = 1$T in the y direction at the bottom of an MH with main axis along the y direction, and (b) only a single magnet with a residual flux density $B_r = 1$T in the y direction.

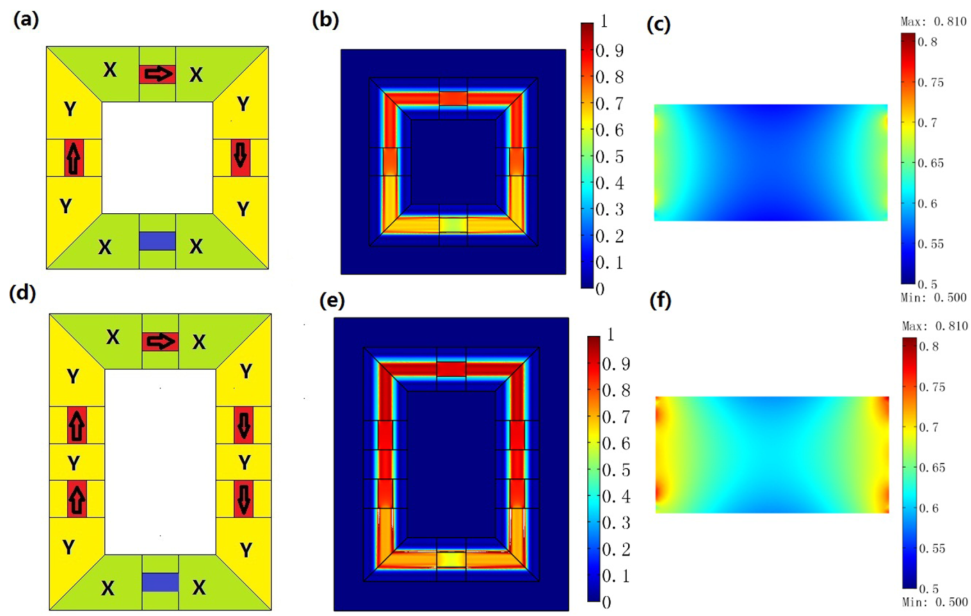

FIG. 2. The fundamental idea of cascade magnets. (a) and (d): three and five magnets are set inside a closed loop composed by the MH, respectively. The magnets are placed in the red regions (the black arrows indicate the direction of the residual inductions). The residual induction of each magnet is chosen to be $B_r = 1$ T. The green and yellow regions labeled 'X' and 'Y' are filled with the MH whose main axes are along the x and y directions, respectively. The blue region is the air region in the loop, within which we get an enhanced DC magnetic field. (b) and (e): numerical simulation results for (a) and (d), respectively. The DC magnetic field in the center blue air region of (b) and (e) is separately plotted in (c) and (f), respectively.

effectively collected in this loop. We also create a region of air inside this loop and can obtain an enhanced DC field within this air region (see Figure 2). To get a higher DC field in the desired air region, we can simply add more magnets into this loop (e.g. we add two more magnets in the loop from Figure 2(a) to 2(d)).

The relation of the center field and the number of magnets cascaded in the loop is shown in Figure 3. We can conclude that as the number of cascaded magnets increases, the field in the air region of the loop also increases.

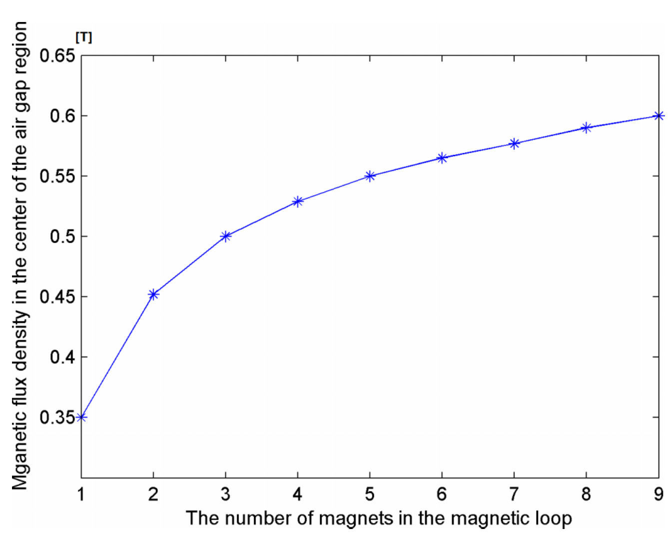

FIG. 3. The relation between the number of magnets in a single magnetic loop and the DC magnetic flux density in the center of the air region in the loop.

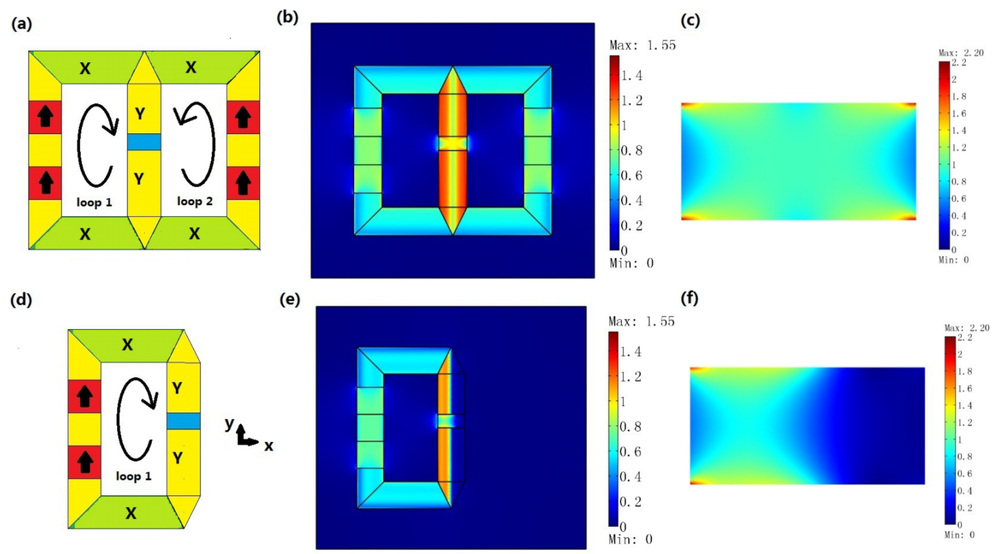

FIG. 4. The essential idea of connecting magnetic loops in parallel: (a) two magnetic loops are connected in parallel, and (d) a single magnetic loop is used. The colored regions in (a) and (d) indicate different media and are consistent with the definitions in Figure 2. Note that the blue region is an air region, in which we obtain an enhanced DC magnetic field. The residual induction of each magnet is still chosen to be $B_r = 1\mathrm{T}$. (b) and (e): the DC magnetic flux density distribution for (a) and (d), respectively.

In addition to cascading magnets in a single magnetic loop (i.e. connection in series), we can also combine many magnetic loops together (i.e. connection in parallel). Figure 4 provides an example of this idea: two magnetic loops are connected to obtain a higher DC field in the center air region (see Figure 4(a)–4(c)) than when a single loop is used (see Figure 4(d)–4(f)). Connecting many magnetic loops in parallel is an efficient way to increase the transverse region of the enhanced field (the direction vertical to the main axis of the MH). We can also connect more magnetic loops in parallel from the perspective of a 3D space (e.g. by rotating the loops in Fig. 4 along the y-axis by a certain angle, we will obtain more loops that can be connected in this system).

As shown in Figure 2 and 4, when the number of magnets in the same magnetic loop or the number of magnetic loops connected in parallel increases, the DC magnetic field in the air gap region is strengthened. At the same time, the DC magnetic field within the MH of the magnetic loops is strengthened. If we want to use magnetic loops to get a stronger DC magnetic field, we cannot simply add more magnets in a single magnetic loop or connect more magnetic loops in parallel due to the fact that the SC, which is the building block of an MH, will no longer work if the applied DC field is too large. However we can use a nested structure to combine the DC magnetic field in many different magnetic loops without increasing the maximal field in a single loop.

IV. NESTED MAGNETIC LOOPS

Besides connecting magnetic loops in series or parallel, we can use another simple method to connect many magnetic loops together, which we call nested magnetic loops (i.e. make many separated magnetic loops sharing a common air gap region). In order to nest many magnetic loops together, we need to introduce more than one air gap region in each magnetic loop. Two simple structures are shown in Figure 5(a) and 5(b): two and three magnetic loops are nested, respectively. Compared with the case of one magnetic loop (the DC magnetic field in the center air gap region is 0.155T), the DC magnetic field in the common center air gap region of many magnetic loops is larger (0.219T and 0.288T for two loops and three loops nested together, respectively). We should note that the DC magnetic field within each magnetic loop is on the order of 0.5T and 0.4T for two and three nested loops, respectively. Thus, when more loops are nested, the DC field in the center

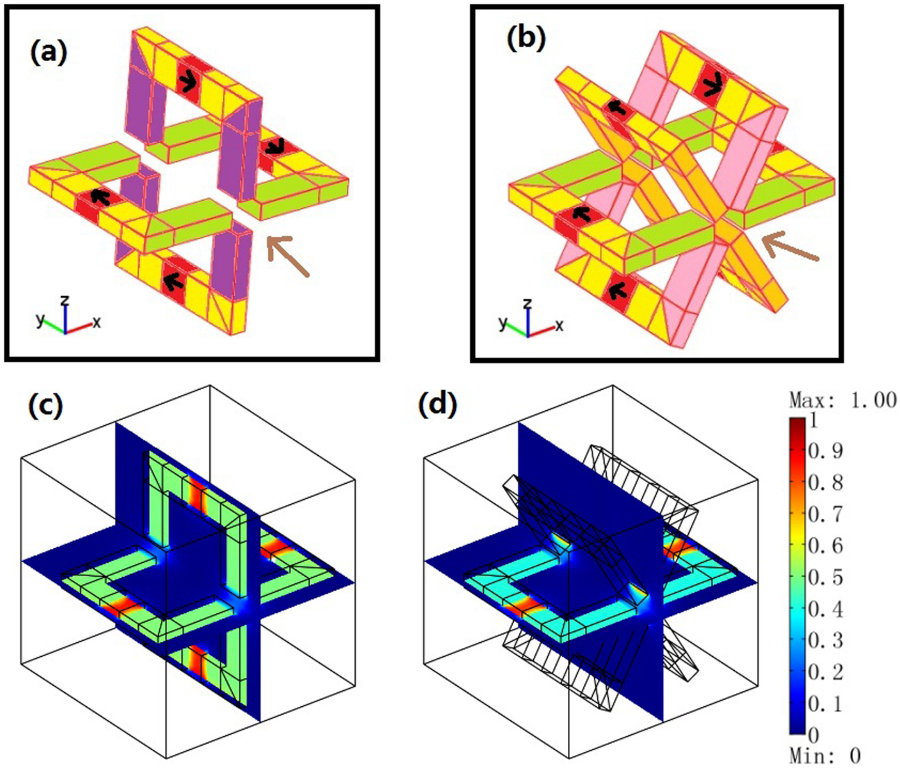

FIG. 5. (a) and (b) show 3D structures for two and three magnetic loops nested together, respectively. Red regions with black arrows indicate the magnets with unit residual flux density $B_r = 1$T along the arrow's direction. Other regions with different colors indicate MHs with main axes in different directions (e.g. yellow, green, and purple regions correspond to main axes along the x, y, z directions, respectively). The brown arrow indicates the common air gap region of these magnetic loops. (c) and (d) FEM simulation results for (a) and (b), respectively: we plot two cross sections (in the x-y and y-z planes) of the amplitude of the magnetic flux density distribution.

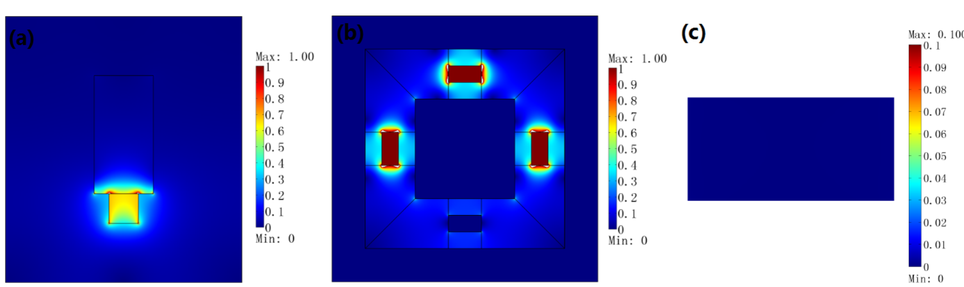

FIG. 6. FEM simulation results: the absolute value of the magnetic flux density distribution (a) when we replace the MH (with a relative permeability of 0.001 along the x direction and 1000 along the y direction) in Figure 1(a) with a high permeability material with a relative permeability of 1000; (b) when we replace the MH in Figure 2(b) by a high permeability material with a relative permeability of 1000; (c) We plot the DC magnetic field in the central air region of (b).

common air region is strengthened, and the DC field in each magnetic loop is weakened, which is what we expect for the application of DC magnetic field enhancement.

V. SUMMARY AND DISCUSSION

Although an MH has been proposed for transferring the DC magnetic field to an arbitrarily-long distance,[14,15] the ideas of the magnetic loop composed by the MH and the nested magnetic loops are first proposed in this paper. Once the magnetic loop is introduced, the DC magnetic field produced by many separated magnets can be utilized more effectively. Furthermore, the idea of the nested magnetic loops gives a novel way to achieve a high DC magnetic field in future (the DC magnetic field in each magnetic loop can be small, and the total superposed DC magnetic field in the common air region can be very large if many magnetic loops are nested together).

We should note that the magnetic loop can also be built by a high permeability material. However, the performance of the magnetic loop composed by a high permeability material is much lower than that of our magnetic loop composed by the MH. As shown in Figure 6(a), a single hose composed by a high permeability material cannot transfer the DC magnetic field to a long distance compared with the case that an MH is utilized (see Figure 1(a)). If we replace the MH in Figure 2(b) by the homogeneous high permeability material, we cannot collect the DC magnetic field effectively in the designed center air region in the loop (see Figure 6(b) and 6(c)).

The MH has been experimentally demonstrated by a ferromagnetic core with a high permeability and a superconductor shell wrapped around a plastic former.[14] The high-temperature superconductor materials and the high permeability ferromagnetic materials are both commercially available (e.g. see our previous experimental results on a DC magnetic concentrator[11]). Refrigeration is required to keep the good performance of the superconductor.

Analogous to the devices for electromagnetic waves designed with TO, TO provides a theoretical tool for extending many novel ideas to DC fields. An MH performs like a 'waveguide' for DC magnetic fields, and similarly a magnetic loop proposed here is similar to a 'cavity' for the DC magnetic field. A magnetic loop can help collect the magnetic flux produced by many separated individual magnets, and achieve an enhanced DC field in an air gap of the loop. Similarly to electronic circuits, the magnetic loops can also be connected in parallel to collect magnetic energy in an air gap region with a larger cross section. To increase the DC magnetic field in the air gap region without increasing the DC magnetic field within the magnetic loop, a nested structure in which many magnetic loops share a common air gap region can be used. The proposed method will have many potential applications, including DC magnetic enhancement, DC magnetic circuits, etc.

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