The Mikaelian's Magnetic Lens for Static Magnetic Field Enhancement

Fei Sun[1, 2] **and Sailing He**[1, 2]

[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), Stockholm S-100 44, Sweden

Abstract— Traditional lenses for static magnetic field concentration are often closed structures and the enhanced DC magnetic fields are inside these structures. The static magnetic flux diverges very quickly in the free space outside these closed lenses. In this paper, we extend the Mikaelian's lens which has been widely used for focusing the light wave to design a non-closed DC magnetic lens which can concentrate the DC magnetic field and give a good DC magnetic field enhancement in free space regions even after a certain distance from the back surface of the lens. Numerical simulations verify the performance of the device.

1. INTRODUCTION AND METHOD

Static magnetic field plays a significant role in many technologies and applications. Achieving an enhanced high DC magnetic field in free space region will lead a revolution in current technologies, e.g., improving the sensitivity of magnetic sensors, improving the medicinal technologies based on drug attached by magnetic nano-particles, and etc.. Magnetic lenses are passive devices which can focus/concentrate the static magnetic field. Many magnetic lenses have been proposed in recent years, e.g., based on the superconductor [1], various structures have been designed to achieve a static magnetic field enhancement in a closed free space region. Based on transformation optics (TO) and DC meta-materials, many novel magnetic lenses/concentrators have been designed within these two years [2–6]. Many of these (superconductor-based or most TO-based) lenses are closed structures, which mean they can only give a good magnetic field enhancement in the free space region inside the lenses. However in many other important applications, we need a non-closed structure/lens to achieve a static magnetic field enhancement in a region without magnetic materials far away from the lens. For example it requires a high strength and high gradient DC magnetic field achieved in a deeper human tissue to control magnetic nano-particles attached with drugs. As the static magnetic field strength falls off very rapidly with distance after the back surface of the active coil or magnet, conventional closed DC magnetic lenses cannot help to overcome this obstacle. A novel non-closed magnetic lens based on finite embedded transformation (FET) has been proposed very recently [3], which has been shown that it can give high DC magnetic field enhancement with high gradient even after a certain distance from the back surface of the lens. However this lens needs inhomogeneous anisotropic magnetic materials, which is very difficult to be fabricated. In this paper, we propose another kind of a non-closed magnetic lens for static magnetic field enhancement. An enhanced magnetic field can be achieved in a region without any magnetic materials after a certain distance (e.g., 5 cm) of the back surface of the lens. Compared with our former design based on FET, the magnetic lens proposed here is not anisotropic, which are easier to be realized.

Mikaelian's lens (ML) is one kind of self-focusing lens [7], which has been widely used in information optics. In this paper we use inhomogeneous magnetic materials of Mikaelian's profile (referred as a magnetic ML) to concentrate static magnetic field. Considering electric field and magnetic field are decoupled in static field's case, we only need permeability to describe the lens. For a two dimensional (2D) case, its geometrical shape is a rectangular with height H, thickness (length along the center axis direction) d and permeability of the lens can be given as:

$$\mu = \mu_c \mathrm{sech}(gy) \tag{1}$$

We have assumed that x axis is the magnetic ML's center axis in above expression. μ_c is the permeability in the center axis of the lens. g determines the speed of gradual changes in permeability of the lens in y direction. Larger g means permeability decreases faster from the center to the edge of the lens. $\operatorname{sech}(x)$ is the hyperbolic secant function. Next we will use finite element method (FEM) to study the performance of magnetic ML for static magnetic field enhancement. First we study a single 2D magnetic ML placed in a uniform background DC magnetic field with amplitude 1 T. As we can see from Figs. 1(a), (b) and (c), the magnetic flux is attracted to the center part of the magnetic ML due to the fact that permeability of the magnetic ML increases from the edge to its center. Compared with Figs. 1(a) and (b), we find that if other parameters keep the same, the higher height H of the magnetic lens, the larger field enhancement. We should note that if the height of the lens is larger, the permeability at the edge of the lens will approach infinitely small. Other studies have shown that it can achieve a DC magnetic field enhancement at the edge of materials with permeability $\mu \to 0$ [5], which is the reason why we can obtain a field enhancement at the edge of our lens. We can simply use a superconductor with ideal permeability $\mu = 0$ for DC magnetic field to achieve a good magnetic field enhancement. However for a single superconductor, the enhanced DC magnetic field is mainly at the geometrical singularity points or edges of the structure (similarly to the edges of our ML device). In many applications, we need an enhancement in the same direction of the background incident DC magnetic field and even after a certain distance from the back surface of the lens. Our magnetic ML can achieve this requirement: The enhancement field is in the same direction of the external incident magnetic field and the enhancement is still obvious even after a certain distance from the back surface of our lens (e.g., 5 cm after the back surface of the lens, the field enhancement on the center axis of the lens is about

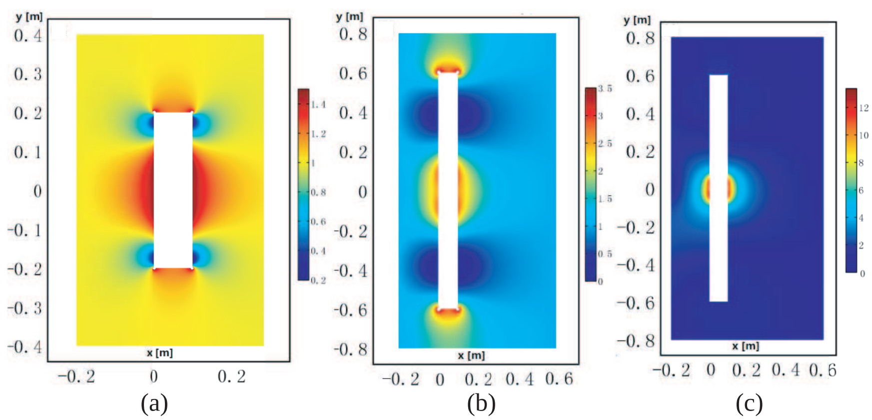

Figure 1: 2D FEM simulation results: The amplitude of total static magnetic field distribution when a uniform background DC magnetic field with amplitude 1 T is normally imposed onto the lens from $-x$ to $+x$ direction. The white rectangular region is the magnetic ML. The parameters of the magnetic ML: (a) $H = 0.4\,\text{m}$, $d = 1\,\text{cm}$, $\mu_c = 10$ and $g = 30\,\text{m}^{-1}$. (b) $H = 1.2\,\text{m}$, $d = 1\,\text{cm}$, $\mu_c = 10$ and $g = 30\,\text{m}^{-1}$. (c) $H = 1.2\,\text{m}$, $d = 1\,\text{cm}$, $\mu_c = 10$ and $g = 80\,\text{m}^{-1}$.

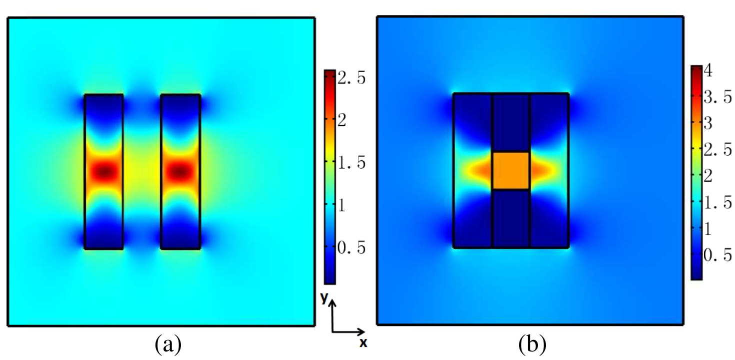

Figure 2: 2D FEM simulation results: The amplitude of total magnetic flux density distribution when a uniform background DC magnetic field of amplitude 1 T is normally imposed onto the structure from $-x$ to $+x$ direction. (a) The structure is two identical magnetic MLs with the same parameters of the one in Fig. 1(a) separated by 10 cm. (b) The structure is composed of two diamagnetic materials with height 15 cm in y direction, width 10 cm in x direction and permeability $\mu = 0.01$ placed between two identical MLs used in Fig. 2(a).

1.25, 1.98 and 5.15 in Figs. 1(a), (b) and (c) respectively). g determines the speed of gradual changes in permeability of the magnetic ML. Comparison between Figs. 1(b) and (c) shows if other parameters keep the same, the larger g the higher field enhancement.

If we add another identical magnetic ML after a certain distance from the first one, we can obtain a further degree of magnetic field enhancement. As shown in Fig. 2(a), two identical magnetic MLs with the same parameters of the one in Fig. 1(a) (separated by 10 cm) are placed in a uniform DC background magnetic field of amplitude 1 T. In this case the DC magnetic field enhancement on the center axis 5 cm after the back surface of the first lens is about 1.54 (one single lens can only achieve a 1.25 time field enhancement in Fig. 1(a)). We also study a case that if we add some additional structures to our double magnetic MLs in Fig. 2(a) to get a better magnetic field enhancement with a high uniformity. As shown in Fig. 2(b), we add two diamagnetic materials with permeability $\mu = 0.01$ in the middle of our two identical MLs, we get a nearly uniform 2.83 time of magnetic field enhancement in a 10 cm plus 10 cm rectangle air region.

2. SUMMARY

Based on Mikaelian's lens (ML) which has been widely used to focus the light wave, we proposed a magnetic ML for static magnetic field enhancement. The proposed magnetic ML has many special features: First the field enhancement factor can be tuned by changing parameters of the ML (e.g., g and μ_c). Second the enhancement is not only near the surface of the lens but also after a certain distance of from the lens (e.g., 1 cm to 5 cm). Third we can achieve higher enhancement degree with high uniformity by combining our magnetic ML with some other structures. Our magnetic ML will have many potential applications in magnetic sensors, wireless energy transmission and drug delivery by magnetic particles.

ACKNOWLEDGMENT

Fei Sun thanks the China Scholarship Council (CSC) for the support (No. 201206320083).

REFERENCES

1. Zhang, Z. Y., S. Choi, S. Matsumoto, R. Teranishi, G. Giunchi, A. F. Albisetti, and T. Kiyoshi, "Magnetic lenses using different MgB2 bulk superconductors," *Supercond. Sci. Technol.*, Vol. 25, 025009, 2012.
2. Sun, F. and S. He, "Create a uniform static magnetic field over 50 T in a large free space region," *Progress In Electromagnetic Research*, Vol. 137, 149–157, 2013.
3. Sun, F. and S. He, "Static magnetic field concentration and enhancement using magnetic materials with positive permeability," *Progress In Electromagnetic Research*, Vol. 142, 579–590, 2013.
4. Sun, F. and S. He, "DC magnetic concentrator and omni-directional cascaded cloak by using only one or two homogeneous anisotropic materials of positive permeability," *Progress In Electromagnetic Research*, Vol. 142, 683–699, 2013.
5. Navau, C., J. Prat-Camps, and A. Sanchez, "Magnetic energy harvesting and concentration at a distance by transformation optics," *Phys. Rev. Lett.*, Vol. 109, 263903, 2012.
6. Sun, F. and S. He, "Novel magnetic lens for static magnetic field enhancement," *PIERS Proceedings*, Stockholm, Sweden, 1689–1691, Aug. 12–15, 2013.
7. Sun, F., Y. G. Ma, X. C. Ge, and S. He, "Super-thin Mikaelian's lens of small index as a beam compressor with an extremely high compression ratio," *Optics Express*, Vol. 21, No. 6, 7328–7336, 2013.