Analysis of magnetic systems with high-anisotropy localized magnetic field for terahertz-radiation generation

S E Azbite A Kh Denisultanov and M K Khodzitsky

Department of Photonics and Optical Information Technologies, ITMO University, 49 Kronverksky av., St. Petersburg, Russia
E-mail: azbite@mail.ru

Abstract. For enhancement of terahertz radiation generation in terahertz devices four permanent magnetic systems by strong localized magnetic field were considered. Their different configurations were used for simulation and comparative analysis and choice compact system with maximum value of localized magnetic field at the room temperature.

1. Introduction
At the present time scientific researches in terahertz frequency range attract more interest. Terahertz radiation may be applied for biomedicine, non-destructive examination, security system, spectroscopy, etc. There are various terahertz (THz) radiation generation systems which use magnetic field for efficiently generation. Rungsawang et al. [1] theoretically described the THz electromagnetic radiation originating from spins in CdMnTe diluted magnetic semiconductor quantum wells. Kumar et al. [2] examined terahertz generation at the beat frequency of two lasers in the presence of transverse magnetic field. Also an optimization of magnetic field is an important aspect [3]. Weiss et al. [4] applied an external magnetic field for increasing of the generated THz radiation power in semiconductor materials. Currently, superconductor and permanent magnetic systems are used. Strong magnetic field superconductor systems need cooling and power source whereas permanent magnetic systems operate at room temperatures and produce small magnetic fields [5]. This paper represents the research of compact permanent magnetic systems with strong magnetic field at room temperature.

2. Description of magnetic systems under study
For this research four magnetic systems were considered. These systems have various segmental configuration: system of two magnets, Halbach cylinder, four-segment cylinder and hemisphere with cone. Each of these systems was calculated for NdFeB that is a material with a giant magnetic anisotropy, its magnetization, $M_s$, is 1280 Gs. Due to use this material a strong localized magnetic field can be obtained at room temperature. The magnetic field strength distribution depends on magnet geometrical parameters. Theoretical investigation was performed in the papers [6], [7]. The first system consists of two parallelepipeds without a gap, which have with the opposite magnetization direction. 3D model is shown in Fig.1. The vertical
component of stray field, \( H_z \), is:

\[
H_z(x, y) = 2M_s(\arctan \frac{a+x}{z} - \arctan \frac{a-x}{z} - 2 \arctan \frac{x}{z}),
\]

(1)

It is seen that \( H_z(x, z) < 2\pi M_s \) and it yields a small contribution in a total field \( H = (H_x^2 + H_y^2)^{1/2} \). \( H_x \) component of stray magnetic field at \( b \gg a \) is determined by the expression:

\[
H_x(x, y) = 2M_s[\ln((a^2 + z^2 + 2ax + x^2) - 2\ln(x^2 + y^2) + \ln((a^2 + z^2 - 2ax + x^2))],
\]

(2)

In the case \( x < 0.01a \) and \( z = 0 \) we can write \( H_x(x) \simeq 4M_s \ln(a/x) \) The second system consists of four triangular prisms it has a cavity near point \( O \). Practically, it is the simplest Halbach cylinder. 3D model is shown in Fig.2 On the gap edges the singular points exist. Their coordinates are \( z = 0 \) and \( x = \pm \delta \). In these points magnetic field attains the largest value. The expression for \( H_x \) has the form

\[
H_x(x, z) = M_s[\ln((a+\delta+x)^2+z^2) + \ln((a+\delta-x)^2+z^2) - \ln((\delta+x)^2+z^2) - \ln((\delta-x)^2+z^2)]
\]

(3)

After an algebraic transformation we can write for field strength in narrow gap

\[
H_x(n) = 8M_s \ln \frac{R}{r} \sin \frac{\pi}{2n}
\]

(4)

The third system is a cylinder that consists of four equal segments. It is shown in Fig.3 For system, which consists of several charged surfaces, the magnetic field attains the largest value. In paper [7] it was shown that for obtaining maximum value of magnetic field it is necessary magnetization vector is centrally directed along bisector. Charge density at both surface is
Figure 3. Cylinder made as four equal segments, radius $R$ is 50 mm, magnetization vector is centrally directed along bisector.

$\sigma_{xz} = \sigma_{xy} = \sqrt{2}M_s$. Total field is sum of linear fields. It possesses maximum value near point O and may be described by equal

$$H_z \simeq 2nM_s \sin \frac{\pi}{n} \ln \frac{h}{r} \quad (5)$$

$r = (x^2 + y^2 + z^2)^{1/2}$ is the distance of a point from the origin to observer point, $h$ is the cylinder height. For four sectors we obtain

$$H_z \simeq 4\sqrt{2}M_s \ln \frac{h}{r} \quad (6)$$

The fourth system is cone in hemisphere, which is divided by radial planes passing through the cone axis (Fig. 4) In each of the sectors the vector $M_s$ lies in the plane passing through the

Figure 4. Hemisphere is divided by radial planes it has a hole with cone; radius $R$ is 50 mm, vertex cone angle $\alpha$ is 54°. Magnetization vector lies in the bisector plane for each magnet and makes an angle with axis $z$ equal $\varphi_1 = -107^\circ$ for cone and $\varphi_2 = 14^\circ$ for segments of hemisphere.

bisector and it is directed along to the normal to cone surface [7]. $H_x$ component of magnetic field is

$$H_x \simeq 0.77M_s[\sin \varphi_1 \sin \alpha + \sin \varphi_2(1 - \sin \alpha)] \ln \frac{R}{r}, \quad (7)$$

where $\alpha = 54^\circ$, $\varphi_1 = -107^\circ$, $\varphi_2 = 14^\circ$. That system is source of strong magnetic field of point type. In all points inside the magnet strong magnetic field is at right angle to magnetization vector, therefore possibility of magnet demagnetization by generic field is lower. One can use this system for obtaining of strong stray field.
3. Estimation and simulation
Optimum parameters was matched for these systems, like size, quantity of segments and direction of magnetization vector for composite system. The dimensional parameters were calculated for an operating terahertz pulsed spectrometer consistent with design compactness and strong localized magnetic field capability system for obtainment of known beforehand magnitude and magnetic field strength distribution. The dependence of magnetic field strength on magnet characteristics (like magnetization, magnet dimension, gap between plates) was analytically calculated by Matlab. Each of four systems was simulated by COMSOL MultiPhysics software using AC/DC Module. Two magnets with the opposite magnetization direction have a strong localized magnetic field in the region from -2 till 2 mm, it is above $2 \times 10^4$ Oe (Fig. 5) This system has magnetic field along line of contact of both magnets. Halbach cylinder has a strong localized magnetic field in singular points on gap edges. We can obtain magnetic field value above $2.3 \times 10^4$ Oe in over the range 2 till 2 mm (Fig. 6). Four-segment cylinder has a strong localized magnetic field near point O, in the region from -2 till 2 mm, it is above $2.5 \times 10^4$ Oe. (Fig. 7) The cylinder is source of strong magnetic field of point type. Hemisphere, divided by radial planes, with cone has a strong localized magnetic field near point O, it is above $3 \times 10^4$ Oe within the interval from -4 till 4 mm. (Fig. 8). Also the hemisphere is source of point type magnetic field. The system consisting of two same uniaxial magnets with opposite magnetic field strength direction allows obtaining twofold magnetic field strength compared to one magnet case.

Figure 5. Distribution $H_x(x, y)$ at $z = 0$ in the two magnets system: a) in all xy-surface (simulated in COMSOL); b) in the region of $-2 < x < 2$ mm (simulated in Matlab).

Figure 6. Distribution $H_{total}(x, y)$ at $z = 0$ in the Halbach cylinder system: a) in all xy-surface (simulated in COMSOL); b) in the region of $-2 < x < 2$ mm (simulated in Matlab).
Figure 7. Distribution $H_z(x, y)$ at $z = 0$ in the four-segment cylinder system: a) in all xy-surface (simulated in COMSOL); b) in the region of $-2 < x < 2$ mm (simulated in Matlab).

Figure 8. Distribution $H_z(x, y)$ at $z = 0$ in the hemisphere, divided by radial planes, with cone system: a) in all xy-surface (simulated in COMSOL); b) in the region of $-5 < x < 5$ mm (simulated in Matlab).

Comparison of the two magnets system and the Halbach cylinder was made (Fig. 9). It is seen that magnetic field of the Halbach cylinder is lower than field of two magnets system, it is above $2.3 \times 10^4$ Oe in region from -2 till 2 mm and practically uniform field from -0.5 till 0.5 mm. Two magnets system magnetic field is above $2.5 \times 10^4$ Oe on the interval from -1 till 1 mm. Thus the two magnet systems can be used for a measurement near axis $x = 0$, and the Halbach cylinder system can be useful for enhancement of THz generation using small square samples. On the results of comparative analysis of the four-segment cylinder and the hemisphere, divided by radial planes, with cone (Fig. 10) one can see that magnetic field of the hemisphere is higher.

Figure 9. Comparison of the two magnets system (blue line) and the Halbach cylinder (red line) at $z = 0, y = 0$. 
and reaches value $H$ above $3 \times 10^4$ Oe in the interval from -3 till 3 mm, whereas the magnetic field of the cylinder is above $2.5 \times 10^4$ Oe in this region. The hemisphere yields the highest magnetic field strength while it has elaborate design. On the results of analytical estimation, simulation and comparison the hemisphere with cone was selected as the most effective compact system.

![Comparison of the four-segment cylinder (blue line) and the hemisphere with cone (red line) at $z = 0, y = 0.$](image)

Figure 10. Comparison of the four-segment cylinder (blue line) and the hemisphere with cone (red line) at $z = 0, y = 0.$

4. Conclusions
In conclusion, the magnetic systems with high localized magnetic field were investigated. Due to these systems made from NdFeB that is material with giant magnetic anisotropy, the high magnetic field is possible. Each of magnetic systems was estimated and simulated. The two magnets system and the simplest Halbach cylinder yield low magnetic field strength and may be used for enhancement of THz generation using small oblong or square samples respectively. By the four-segment cylinder and hemisphere, divided by radial planes, with cone we can obtain higher magnetic field strength. The cylinder is easy to develop, but its magnetic field strength localizes in a narrow area. The hemisphere has an elaborate design and produces strong magnetic field in relative wide area. As the result of this research the hemisphere with cone was selected for obtaining strong magnetic field above $3 \times 10^4$ Oe in the region from -3 till 3 mm.

Acknowledgments
This work was financially supported by Government of Russian Federation, Grant 074-U01.

5. References
[1] Rungsawang R et al. 2013 Phys. Rev. Lett. 110 177203
[2] Kumar et al. 2012 J. of Phys. and Chemis. of Solid. 73 pp 269-274
[3] Malik A et al 2012 Phys. Rev. Lett. 85 016401
[4] Weiss C, Wallenstein R and Beigang R 2000 Appl. Phys. Lett. 77 pp 4160-4162
[5] Bespalov V et al 2008 J. of Opt. Tech. 75 pp 636-642
[6] Samofalov V, Belozorov D and Ravlik A 2006 The Phys. of Met. and Metallogr. 102 pp 494-505
[7] Samofalov V, Belozorov D and Ravlik A 2013 Physics -Uspekhi 56 pp 269-288