A four mirror-current planes model for the gradient field enhancement in a permanent magnet

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Introduction Magnetic field gradients produced by gradient coils in permanent magnets are enhanced by magnetic materials. This enhancement mechanism has been explained by a mirror-current theory with two mirror-current planes [1]. However, we found that the enhancement of gradient fields can not be explained by conventional mirror-current theory [2]. Here, we measured and calculated the magnetic field gradients produced by a planar gradient coil set in the gap space of a permanent magnet and found that the four mirror-current planes could explain the enhancement mechanism.

Theory When gradient coils are mounted on the pole piece of a permanent magnet, the magnetic field on the surface of the pole piece is theoretically vertical to the pole piece surface. Hence, the enhancement mechanism can be modeled using mirror currents. We modeled the enhancement effect using four mirror-current planes, as follows (FIG. 1):

$$\vec{J}_s(\vec{r}) = \vec{J}_+(\vec{r})\delta(z-a) + \vec{J}_{m1+}(\vec{r})\delta(z-(2d-a)) + \vec{J}_{m2-}(\vec{r})\delta(z-(2d+a))$$
$$+\vec{J}_-(\vec{r})\delta(z+a) + \vec{J}_{m1-}(\vec{r})\delta(z+(2d-a)) + \vec{J}_{m2+}(\vec{r})\delta(z+(2d+a))$$
$$(\vec{J}_{m1\pm}(\vec{r}) = \vec{J}_{m2\mp}(\vec{r}) = \alpha\vec{J}_\pm(\vec{r}), \quad \alpha \le 1)$$

where α is the relative mirror-current amplitude.

Materials and methods We used an MRI permanent magnet with a four-column yoke for the experiment (FIG. 2). The permanent magnet had field strength of 0.3 T, its d was 85.6 mm, diameter of the pole piece diameter was 42.5 cm, and its homogeneous volume was 22 cm × 22 cm × 8 cm dev (diameter ellipsoidal volume). A planar gradient coil set (FIG. 3) was designed using the target field method and a genetic algorithm. The design parameters were as follows: magnet gap = 13 cm, target volume = 22 cm × 22 cm × 8 cm dev, diameter of the current flow region = 40 cm, number of wire turns was 25 for the Gx and Gy coils and 32 for the Gz coil. The gradient coil set was placed in the magnet gap spaces and the gradient field was measured using an NMR magnetometer (PT2025, Metrolab Instruments S.A., Switzerland). In contrast, the gradient field distributions generated by the gradient coils in the permanent magnet were calculated using the conventional mirror-current and the four mirror-current models. The relative mirror current amplitude (α) was determined for the minimum mean square error of the difference between the calculation and the measurements.

Results and discussion Table 1 shows the efficiency of the gradient coils obtained from the calculation and measurements. Values in the parentheses show the relative mirror-current amplitudes. For the efficiencies of the Gx and Gy coils, the four mirror-current planes model showed better agreement between calculation and measurement than the two mirror-current planes model. For the efficiency of the Gz coil, although the α value (0.9) for the four mirror-current planes model is closer to unity than the α value (0.65) for the two mirror-current planes model, the two models gave nearly identical values. In conclusion, the four mirror-current planes model gives much better results for enhancement of the gradient field comparing with the two mirror-current planes model reported before.

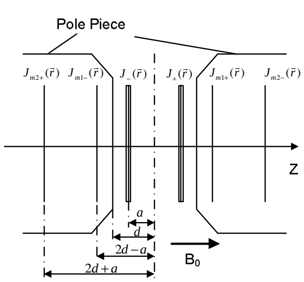

FIG.1

FIG.2

FIG.3

	Measurement	Two mirror-currents model	Four mirror-currents model
Gx	0.179	0.161 (1.0)	0.171 (1.0)
Gy	0.178	0.161 (1.0)	0.173 (1.0)
Gz	0.285	0.286 (0.65)	0.283 (0.9)

Table 1. Gradient coil efficiency (G/cm/A)

References [1] Moon CH et al. Meas Sci Technol 1999;10:136-141. [2] Handa S et al. Proc Intl Soc Magn Reson Med 2005;13:851.