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Simple procedure for the fabrication of flexible NMR shim coils

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ABSTRACT

Photolithography allows simple fabrication of flexible NMR shim coils. Here we demonstrate this procedure by fabricating optimized first-order shim coils for a transverse field orientation "Halbach" permanent magnet cylinder.

1. Introduction

Portable NMR has gained tremendous momentum in recent years thanks to the development of permanent magnets having excellent field uniformity [1–8]. Examples of one-sided portable Magnetic Resonance (MR) tomographs as well as of cylindrical "closed" MR systems are now common. The most convenient approach to design such highly homogeneous systems is to use a spherical harmonic expansion of the main component of the magnetic field [10]. Such an approach allows the design of permanent magnet structures [4,5] and pole pieces [6,7]. The remaining field inhomogeneity usually comes from mechanical and magnetic tolerances, as well as demagnetization that lead to magnetic field profiles that deviate from the theoretical ones. One must thus adjust the magnet (a procedure commonly named "shimming") in order to eliminate at least the first orders in the spherical harmonics expansion of the magnetic field [9]. This may be done by performing small displacement in the magnet pieces or by adding ferromagnetic or permanent magnet material and is called passive shimming [10,11]. However, passive shimming is not enough for achieving high-resolution for spectroscopy and residual field inhomogeneity must be corrected using specially designed electromagnets [9,12]. These are usually placed inside the cylindrical bore of the permanent magnet and are most conveniently fabricated on a flexible substrate that can be rolled on a hollow mandrel. Here we present a very simple procedure to produce lithographically such coils, and we demonstrate experimental results on first-order shims for a cylindrical Halbach permanent magnet [13]. A Halbach cylinder is a special arrangement of permanent magnets that confines the magnetic field in its centre and produces very limited stray field, making it an ideal system for

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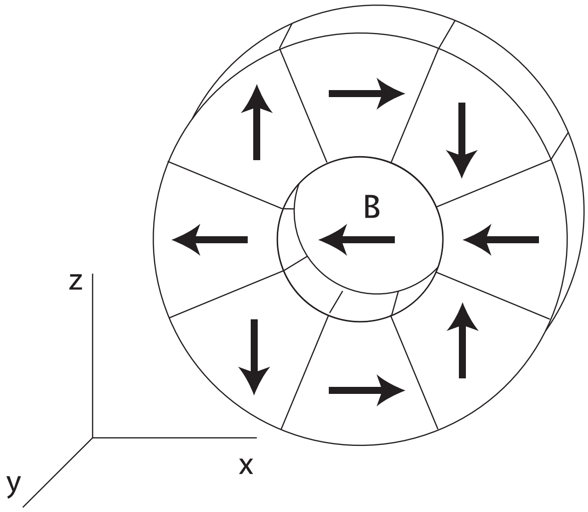

Fig. 1. Schematic diagram of a Halbach dipole cylindrical magnet made of eight segments having a variable direction of magnetization as shown on the diagram. The produced field in the centre of the cylinder is oriented along the *x* axis.

tabletop NMR applications. A schematic diagram of this magnet is shown in Fig. 1.

2. The photolithography process

The photolithography process presented in this work aims at manufacturing flexible copper circuits featuring high spatial resolution. Laser-lathe lithography has been used to micro-fabricate coils for portable NMR [14,15], but here the dimensions of our circuits are much larger than a few millimetres. Compared to direct coil winding by hand or by a machine, it is compatible for batch production with the benefit of error reduction. The copper-clad used features copper – kapton – copper layers of respectively 35 μm – 50 μm – 35 μm of thickness (purchased from Farnell CIF AN210). Such a double-layer substrate presents two advantages. One is to double the efficiency of the coil by printing the pattern twice, while connecting the two layers in series. The second is that it allows the compensation of the necessary connections between the coil turns. The copper clad is flexible enough to wind onto a mandrel of at least 1 cm of radius by hand. This makes it ideal for making shim coils for miniature portable MR magnets. The process can be divided into eight main steps as shown in Fig. 2, where the design of negative patterns of the three shim coils is shown.

Each coil relates to two aligned mask patterns, one of each as shown in the Fig. 3 for upper layers. Both faces were treated at the same time during the process shown in Fig. 2. The design of the coils was performed using an analytical stream function approach [16], which will be described elsewhere [17]. This approach produces curves that define isolated tracks. In order to be able to supply current to each of the tracks, one has to design connections from one track to the next. These connections are made in a symmetric way between the upper and the lower layers of the circuit so their effects on the field homogeneity are cancelled to first order. The design of the coils produced coils that generate first order gradients for the transverse magnetic field B_0 configuration, which are optimized for minimum power dissipation.

For the first step of the coil fabrication, the copper-clad is shaped (cut) to a proper size, leaving a 2-cm margin for easy handling and manipulation. Before processing, it is carefully cleaned by acetone, ethanol, nitrogen and UV ozone cleaning (UVO Cleaner 42 Jelight) for 20 min. The mandrel onto which we wanted to fit

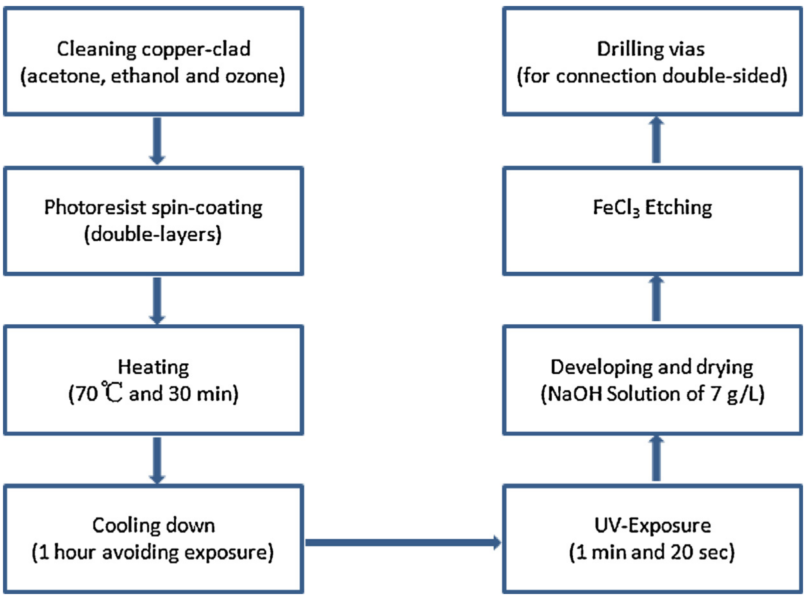

Fig. 2. Process chart of the Shim coil fabrication by photolithography on a flexible substrate.