A Reflection Mode Fiber-optic Faraday Sensor for Device Localization in Interventional MRI

E. N. Aguor[1], S. Brenner[1], R. Umathum[1], W. Semmler[1], M. Bock[1]
[1]Medical Physics in Radiology, German Cancer Research Center, Heidelberg, 69120, Germany

Introduction

In MR-guided interventional procedures instruments such as guide wires, needles or active catheters are used that contain electrically conductive structures. Electric coupling of these structures with the E-field of the transmit rf coil can lead to severe heating which, if the heat is not dissipated, might result in device destruction and could be dangerous for the patient. To reduce device heating several technical measures such as baluns [1] or transformers [2] have been proposed, however, a more safe approach is to avoid conductive structures completely. To this end the concept of an optical sensor for position measurements has been developed [3] that utilizes the Faraday effect to measure the local magnetic field in the MR system during controlled gradient activity.

In the initial design of a fiber-optic sensor laser light was guided to an optically active crystal through an input fiber. The crystal was placed between two polarization foils and the transmitted light was coupled into an output fiber, which was connected to a photo-detector. This set-up could measure both position and orientation in a closed-bore MRI-scanner. To integrate a Faraday sensor into an interventional device (e.g. a 1.3mm-diameter catheter) it would be advantageous to use only one optical fiber for both crystal illumination and signal readout [4]. In this work we present a design for a single-fiber Faraday sensor, which was evaluated in a prototype setup.

Materials and Methods

According to the Faraday effect the polarization of a light beam traversing a magneto-optically active material is rotated, when a magnetic field B parallel to the beam-direction affects the material. Due to the non-reciprocal nature of the effect the rotation is carried on in the same sense when the beam retraverses the material after reflection at its distal end. The net rotation angle is given by $\Phi = V\,L\,B$, where L is the optical path length in the material and the Verdet constant V denotes the material-dependent optical activity. If the optical path deviates from parallelism with the magnetic field direction by an angle α, the effective optical path length is taken into consideration by $\Phi = V\,L\,B\cos\alpha$.

To measure Φ in transmission mode, the material, typically a crystal, is placed in a light beam between a polarizer P and an analyzer A, and Φ is given by the relative angle between P and A at maximum light transmission. At a constant angle of 0° between P and A however, A leads to beam attenuation according to $I(\Phi)=I_0\cos^2\Phi$, where I_0 and $I(\Phi)$ are the light intensities before and after attenuation. To omit the second optical fiber at the end of the crystal a mirror is introduced in place of the analyzer. In this modified Faraday sensor P operates as both polarizer and analyzer. Thus the transmitted light intensity of the sensor becomes

$$I(\alpha) = I_{offset} + I_0 \cdot \cos^2\left(B \cdot L \cdot V \cdot \cos\alpha\right),$$

where I_{offset} describes the constant offset-intensity resulting from light which is reflected before entering the sensor. The prototype of a reflection sensor is shown in Fig. 1. As the magneto-optically active material a 7.5mm-long crystal of terbium gallium garnet (TGG) was chosen with a Verdet constant of 7.2 deg/T/mm at λ = 635 nm [5]. A diode laser (Lasiris PTL-635-3.3, Stocker Yale, USA) was used as light source and the light was guided to the sensor via an optical fiber (core diameter: 63 µm). The light was coupled into the crystal through a ball lens and a polarization foil. A spherically seated, adjustable mirror in the back of the sensor housing reflected the light back into the sensor components and the fiber. On its way back a fraction of the reflected signal light was branched off by a fiber-coupler and measured by a photo-detector. In an initial experiment the reflection mode sensor was placed on the patient table of a commercial whole body 1.5T MR scanner (Siemens Magnetom Symphony). At the magnet's iso-center the sensor was rotated in steps of 5° relative to the B_0-field direction and the photo-detector voltage was measured.

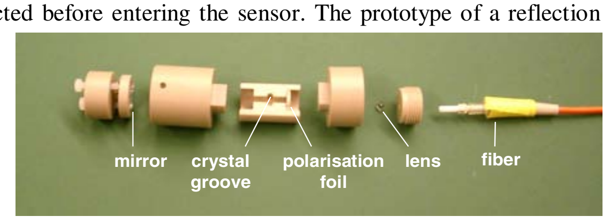

Fig. 1: Exploded view of the reflection mode Faraday position sensor

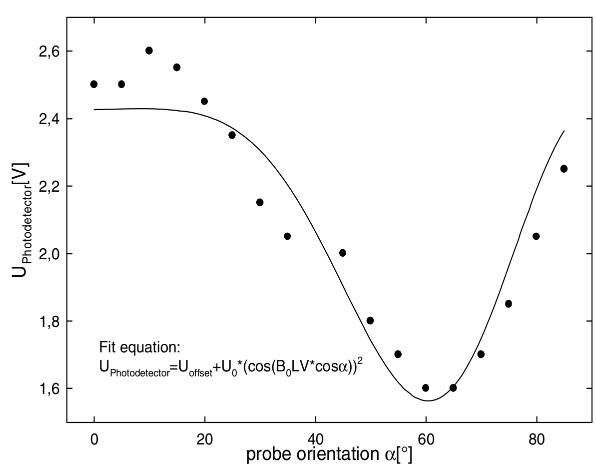

Fig. 2: Photo-detector voltage at different sensor-orientation angles towards B_0

Results and Discussion

The result of the orientation measurement is shown in Fig. 2 together with a parameter fit. In the fit the offset intensity amounted to 62% of the total measured light intensity at α = 0°, and the measured Verdet constant of 8.1 deg/T/mm over-estimates the literature value by 12%. The precision of the measurement is limited by laser light intensity fluctuations, mechanical instabilities and uncertainties in the angle measurement. Nevertheless the measurements show that a reflection-type Faraday sensor can be operated in the MR environment. Future refinements of the setup will aim to increase the mechanical stability to enable position measurements in the gradient field. To achieve a maximum sensitivity of the sensor the crystal length will be adapted so that a Faraday angle of Φ = 45° is realized without gradient activity at parallel orientation to B_0.

References

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