Ultra-sensitive Magneto Optical Fibered Sensors - ULTRAMAGFIBER

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ABSTRACT

We have successfully prepared metal oxide nanoparticles dispersed in a polymer matrix. This material is dedicated to the functionalization of optical fibers for the fabrication of magneto-optical detector. The preparation of the material was achieved via ultimate grinding process and has allowed a stable dispersion of the nanoparticles without the use of any surfactant. The films prepared from this material have demonstrated a Verdet constant of $2.0{\cdot}10^5$ °/(T·m) at 1550 nm. Simultaneously, we have developed a fibered magnetic field detector with a sensing head as small as the fiber itself able to detect values down to 10 µT.

Keywords: Sensor; magneto-optics; optical fiber; nanoparticles; garnet.

1. INTRODUCTION

This project is devoted the development of original processes for the preparation of magneto-optical (MO), polymer dispersed metal oxide nanoparticles (NP), that can be easily deposited on an optical fiber. Thus prepared functionalized fibers are intended to constitute the detection heads of a magnetic field measurement device.

- As dielectric, the optical fibers limit the interactions with the electromagnetic environment and the noise it may induce.
- As no shielding or additional electrical wires are required and as the sensing head is made up of the modified fiber, the footprint of the detector is limited to the size of fiber itself. It is then possible to envision the introduction of the sensor in small devices or in living organisms and measure the magnetic field with a submillimetric resolution.

Originality and innovation point out at the stage of the material preparation and at this of the magnetic field detection setup.

- The MO material is made a dispersion of metal oxide NP in a polymer matrix. The originality lies in the ultimate grinding process used that allows the simultaneous preparation and dispersion of the NP.
- Second, we propose the use of a detection scheme that allows the use of a simple optical fiber just coated with the MO material. In general, the polarization of the light has to be modified in the vicinity of the measurement region and requires additional polarizing elements that expand the footprint of the detector head.
- Additionally, the proposed setup for the measurement of the magnetic field is sensitive to the Faraday effect and to the magnetic circular dichroism (MCD).

We have roughly succeeded in both the tasks planned at the start of the project.

- We are now able to efficiently prepare metal oxide nanoparticles dispersed in an organic (polymer) matrix via ultimate grinding.
- The optical properties of these materials: transparency, scattering and MO, allow the measurement of the Faraday effect in the near infrared (telecom wavelength).
- We have developed the fiberd magnetic field sensor that can use the functionalized fiber. We have demonstrated that the device is able to work on both Faraday effect MCD.

2. STATE OF THE ART

Among the many possibilities offered for the measurement of magnetic fields, those involving optical processes are for now attracting most of the attention. [1] While this devices exhibit extremely high sensitivity, down to the femtotesla, the low level of their saturation field requires the use of shielding. In addition, application of an additional magnetic field, radio frequency signal, or heating may be required in the sensor head region to enable measurement. Therefore, if the optical signal can be carried through an optical fiber, conductive wires are also required to connect the sensor itself to the signal processing device. The introduction of an electrical conductor in a severe electromagnetic [EM] environment is the source of disturbances and noise. By using the MO effect, one can get rid of the conductors and a single optical fiber can carry the signal between the sensor and the signal processing device.[2] Until now, MO measurement has been mainly dedicated to current sensing in the electrical industry, but the development of very high performance MO materials will pave the way for new areas of application. One of the most promising materials is NP metal oxide dispersed in a transparent matrix. [3] Here, the best compromise between MO performance and optical losses can be obtained by adapting the concentration of NP in the transparent matrix. The preparation of such a material usually begins with the synthesis of NP via a bottom-up process (nucleation and growth). The NPs are then functionalized with a surfactant. This is necessary to ensure, at the final stage, homogeneous dispersion in the matrix and to limit aggregation. The opposite, top-down approach is less common but also leads to efficient materials. Here, typically micrometric powders are ground to obtain nanometric particles which are then dispersed in the matrix.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The innovative character of the project lies in the material used, in its preparation process and in the architecture of the optical fiber magnetic field detection device.

The objective is initially to obtain a high-performance MO material that can be easily deposited at the end of an optical fiber. NP cobalt ferrite dispersed in a polymer matrix appears to be a good candidate for early testing. In an attempt to increase the MO response, we doped the cobalt ferrite with ytterbium. We consider the preparation process to be the most original part of this project. We prepare the dispersed NP polymer by ultimate grinding in a ball mill. Once the metal oxide powder is prepared, it is mixed directly with polymer nanospheres in the mill. During this operation, the grain size of the powder is brought to the nanometric range and the NPs thus prepared are efficiently dispersed within the polymer beads without the need for any surfactant. The mixture obtained can be used to coat any optical surface and provide MO properties. In our case, we are interested in modifying an optical fiber in order to prepare a fiber magnetic field detector.

If the coating does not change the size of the fiber much, in general, the size of the sensing head is greatly increased because the measurement of the Faraday effect requires checking the polarization of the light just before the active part MO. The optical elements necessary for managing the polarization have a width of at least a few millimetres when the diameter of the fiber is approximately 100 µm. We propose a detection scheme which avoids this control of the polarization of the light in the measurement zone and thus preserves the small size of the detection head. The footprint of the detector is then limited to the size of the fiber only. The detection device works on the modulation of the polarization of the light before injection into the fiber. It is not only able to detect the polarization rotation induced by the Faraday effect but can also detect the magnetic circular dichroism. It is then conceivable to extend the family of sensitive materials to these MCD materials for the measurement of magnetic fields.

4. PROJECT RESULTS

The procedure of preparation of ytterbium doped cobalt ferrite nanoparticles dispersed in a polymer matrix starts with the synthesis of the Yb: $CoFe_2O_4$ powder by co-precipitation method. The x-ray diffraction (XRD) characterization and SQUID measurements of the powders do not show any clear variation of the lattice parameter or of the magnetization with the amount of ytterbium. Nevertheless, the ytterbium should be effectively inserted in the cobalt ferrite, as no extra phase has been detected in XRD measurements. The powder is mixed with polymer beads, with 70 nm typical diameter, prepared from methyl methacrylate, butylacrylate and diacrylate. The powder/beads blend (1:2.5 ratio in weight) is grinded for 1 hour in the mill with 5 mm zirconia beads. Some water is added to reduce the viscosity and ease the coating on glass substrate via doctor blade or Meyer rod methods. The images of the material obtained by scanning electronic microscopy (SEM) demonstrate that the grinding produces metal oxide NP with sizes below 100 nm and efficiently disperses them among the polymer beads (see Fig. 1).

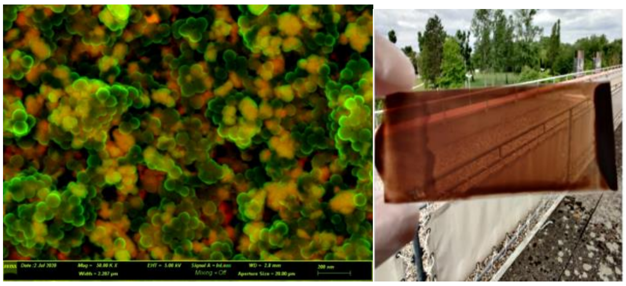

Fig. 1. Left: SEM image in false colors of cobalt ferrite NP (yellow/red) dispersed among polymer beads (green). Right: a layer of 5 µm of composite deposited on a BK7 glass plate and demonstrating low scattering.

The diffusion of the light in the visible range appears to be low, suggesting that the scattering losses would be even more limited in the near infrared. The MO of the material properties at saturation of the magnetization, both the Faraday rotation (FR) and the Faraday ellipticity (due to MCD), are characterized in the visible range (see Fig. 2), and at 1310 nm and 1550 nm.

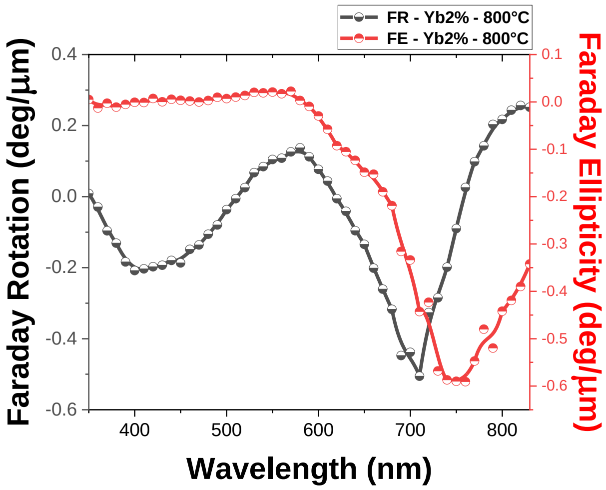

Fig. 2. FR and FE spectra at saturation for $CoFe_2O_4$ nanocomposite film on glass substrate with Yb 2%, annealed at 800 °C for 10 hours.

At these last wavelengths, the FR was measured to be respectively $1.5 \cdot 10^4$ °/(T·m) and $2.0 \cdot 10^5$ °/(T·m) at saturation (around 0.5 T), which compare satisfactorily with the data found in the literature. [4] The next task of this project is the deposition of the polymer dispersed NP at the end of an optical fiber to fabricate the magnetic field sensing head. A first attempt is illustrated on Fig. 3.

This task is still under development as we are facing adhesion problem and trying to extend the thickness of material to get higher sensitivity.

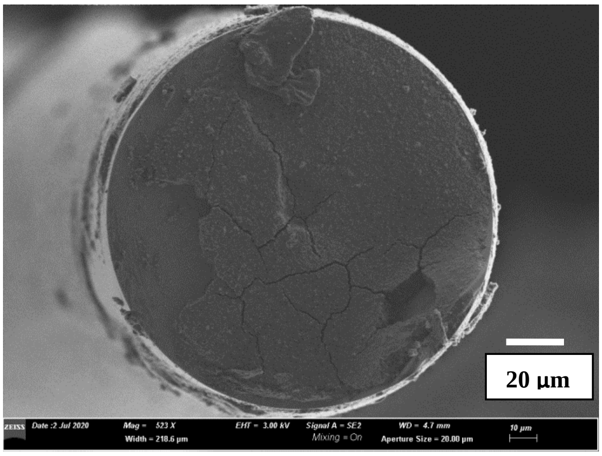

Fig. 3. SEM images of the optical fiber's end coated with cobalt ferrite NP dispersed in polymer beads.

Then to perform the demonstration of the fiberd magnetic field detection device, we have used some previously developed material. The optical fiber is coated with MO bismuth doped yttrium iron garnet (Bi:YIG). The layer is prepared by metal oxide decomposition directly on the fiber itself [5] and then covered with a gold film to increase the reflectivity. The measurement setup is powered by a doubled cw Nd:YAG (532 nm) providing a linearly polarized light beam. This polarization is modulated at 20 kHz by the photoelastic modulator (PEM) before the injection of the light into the polarization maintaining fiber. The light is guided in the fiber to the garnet at its end. It is then reflected back, its polarization modified by the Faraday effect in the double pass through the garnet. The back reflected light exits the fiber and its polarization is analysed by a polarizer and two detectors synchronized with the frequency of the PEM.

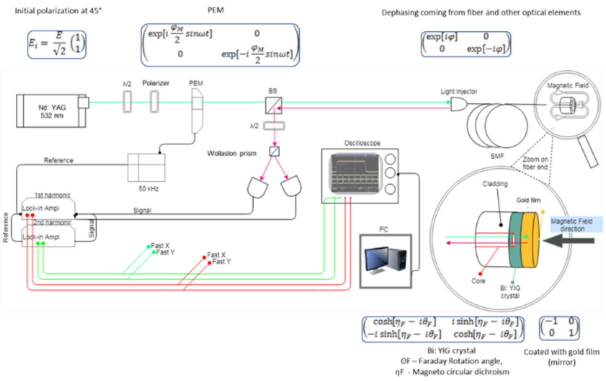

Fig. 4. Schematic of the fibered magnetic field detection device. The matrices and vectors correspond to the Jones elements of the optical components.

The response of the device is characterized applying a magnetic field modulated at 23 Hz at the end of the optical fiber. The result of the measure is given Fig. 5, demonstrating that the expected linear response is effectively obtained and that the measure of a few tens of µT is easily achieved.

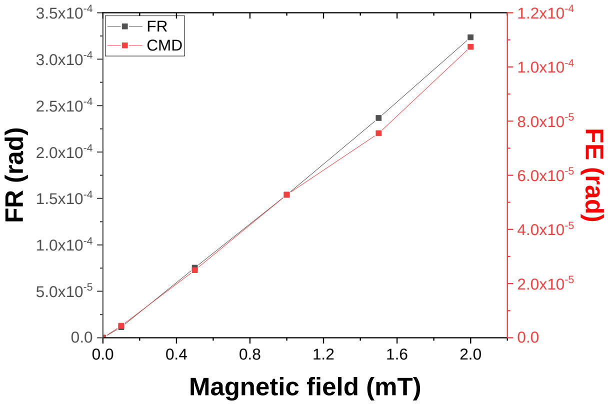

Fig. 5. FR and FE dependency on the amplitude of the magnetic field.

By removing the final polarizer, one can measure simply the variation of the intensity of the back reflected light due to the MCD and measure the amplitude of the magnetic field.

To conclude, we have, on one side, the material sensitive in the near infrared and, on the other side, the setup working in the visible. Our concern is thus naturally to associate both these results and improve the sensitivity of the measurement setup.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

Here, as the demonstration of the magnetic detection is actually carried out, we consider that TRL 4 is fully reached as we are effectively able to detect the magnetic field with our material deposited at the end of an optical fiber. Improving the TRL will now require extensive technical skills. The detection setup has to be fully integrated as well at the optical level (fully fibered circuit has to be developed) as the signal processing one (development of dedicated electronic board). More basically, the implementation of new materials to improve the performances will be of great importance in order to extend the field of application. The protection of the sensitive part (encapsulation, coating…) has to be carefully considered in correlation with the final user's requirements.

5.2. Project Synergies and Outreach

The future of the project has to be considered as well at the scientific/technical development as at the applications and commercial level. As the project stems from an academic lab, well trained in finding partnerships, we will call on a wide panel of academic labs and small companies in Europe possessing the specific skills needed to upgrade and adapt efficiently the device to the market needs. The improvement of the performances and reliability of the device will naturally raise the TRL. Nevertheless, a first industrial partner, able to define a set of technical requirements for a specific application is necessary. The demonstration of this first prototype will be the stepping stone for the development and commercialization of our technology. The identification of such a partner will be carried out by a "commercial engineer" working within the framework of the project and in collaboration with the various organizations in charge of technology transfer. His/her task will be to carry a survey of the potential market, in order to identify the most relevant industrial partners, to contact them and define the scope of the collaboration.

A first focus will be made on medical applications and especially on magnetoencephalography. We are confident that the sensitivity of our devices will match those required for this application and that we can bring real improvements to the current technology. A success in that field will guaranty the dissemination of our work and the development of new applications.

5.3. Technology application and demonstration cases

The detection / measurement of the magnetic field by magneto-optical effect has various advantages when it is associated with optical fibers. The very high dynamics of the MO effect and the high saturation value made the measurement possible even in a volume unshielded against external magnetic fields. Measurements can be performed at room temperature in a normal atmosphere. Since optical fibers are made of dielectrics, they have an extremely low impact on the EM environment. Conversely, the information being carried by photons, the EM environment induces very low noise on the signal, even without any shielding. Crosstalk between fibers is also avoided allowing parallelism of transmission. The size of the fiber (< 100 µm) allows its introduction in very small volumes and in particular in biological organisms. The fields of application of high sensitivity and high resolution magnetometry are particularly broad, including medicine, geology, automotive, power industry, defence and more. As said previously, we will favour medical applications because they require the highest level of performance and therefore give the best proof of effectiveness.

5.4. Technology commercialization

The technology commercialization will depend of the industrial partners we will be able to integrate in our project. The device itself is a sensor and it will find mainly its raison d'être as a part of an apparatus that will conditioned its commercialization.

5.5. Envisioned risks

Considering our results and those presented in the literature, we are confident about reaching the performances required by the envisioned applications. The main risks lie in the competition of our solution with the other technology already in use.

5.6. Liaison with Student Teams and Socio-Economic Study

The liaison with MSc can be considered at two levels. As a laboratory associated with the Université de Strasbourg, we are familiar with the work with student and we propose internships for MSc students. Also interacting with the Télécom Physique engineer school, it will be possible to propose a so-called: "micro project" to these students, generally very interested in activities associating research, development, market survey and communication.

For the socio-economic study, we propose to involve the person recruited for the non-technical tasks of the project. As his/her will gather and distribute the information among the consortium, he/she will be naturally designated to bring the data to the ATTRACT organization.

6. ACKNOWLEDGEMENT

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