Optical fibre magnetofluidic sensors and actuators

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***Abstract* – We review work on magnetofluidic sensors and actuators utilising ferrofluids as transducing elements while being implemented in standard and microstructured optical fibers (MOFs), defining a new kind of optofluidic photonic devices. The concept and design parameters of magneto-fluidic and -viscosity based magneto-meters and modulators will be presented, with particular emphasis given in devices using MOFs as optical interrogation platform.**

I. INTRODUCTION

Photonic Crystal Fibres (PCFs) and generally Microstructured Optical Fibres (MOFs) combine optical and microfluidic functionalities in a single photonic platform; these can be the backbone elements for the further development of the lab-in-a-fiber platform [1]. There have been several examples where liquid and gaseous media have been infiltrated and manipulated inside PCFs and MOFs for the development of sensing, actuating and light emitting/converting applications [2, 3]. We have infiltrated for the first time ferrofluids inside the capillaries of PCFs and MOFs for developing a new kind of magneto-driven/sensitive optical fibre devices [4-7]. Ferrofluids are stable suspensions of colloidal ferromagnetic nanoparticles dispersed into non-magnetic carrier liquids, while being sensitive to the external magnetic field perturbations by means of viscosity, volume, polarization, absorption loss and refractive index changes [8-11]. In addition, ferrofluids exhibit high viscosities and optical absorption rendering their implementation into photonic systems a quite challenging technical task. For this reason most of the sensing and actuating examples presented until now, utilise the ferrofluidic matrices as out-cladding media of optical fibres, where evanescent components of the cladding modes probe refractive and loss changes of the ferrofluids under magnetic field stimulus [12-16]. The confinement of ferrofluids inside the micrometric diameter capillaries of the PCFs and MOFs also induces other surface affinity and fluidic friction effects, which in turn can be tuned upon application of magnetic field and its directional characteristics [17, 18].

Herein we review sensing and actuating examples related to the implementation of ferrofluids inside PCFs and MOFs, as well as, in standard step index fibres. The examples presented below illustrate the potential between the fusion of optical fibre components with ferrofluids (and in general magnetosensitive fluids) for the development of sensing probes and actuators for diverse types of applications [19-22].

II. EXPERIMENTAL

Commercially available PCFs and custom made MOFs were used in the experiments performed. The first MOF used had been drawn by ACREO AB, while had 5 holes of 20.8μm diameter, forming an outer core of 16.1μm, which includes a 3.5%wt Ge doped socket of diameter 8.5μm; this is a grape-fruit shape MOF. In that fibre a 4mm long Bragg grating was inscribed using a 1067.73nm phase mask and a 193nm excimer laser [4]. The grating reflected two major modes, located at 1545.57nm (0^{th} order) and 1541.26nm (1^{st} order), with strengths 12dB and 2.6dB, respectively. The commercially available (Kyriama Pty Ltd, Australia) polymer MOF used had a typical hexagonal hole arrangement, with a core diameter of 6.75μm, hole pitch 4.5μm, and radially variable hole diameter, with innermost ring being ~2.25±0.05μm and following three rings being 2.0±0.1μm in diameter, approximately. The final two outer rings exhibited varying diameters between ~1.5μm and 2.1μm. The fibre is made from polymethylmethacrylate (PMMA), having a refractive index of n_{PMMA}~1.49 @ 587.5nm, with polycarbonate jacket. The commercial hydrocarbon based ferrofluids EMG905 and EFH1, both manufactured by Ferrotec were used. The EMG905 ferrofluid exhibits a 40mT saturable magnetization, 9mPas viscosity, while the EFH1 40mT and saturable magnetization, 6mPas viscosity; in both the carrier liquid is a synthetic isoparaffinic solvent. The EMG905 ferrofluid absorption loss at 1550nm was measured to be 6.84μm^{-1}, while its refractive index was measured to be 1.58±0.01; similar data hold for the EFH1 [7]. Finally, the a water based ferrofluid EMG 605 was used, that has a 22mT saturation magnetization, 5 mPas viscosity, and a refractive index of ~1.4.

III. DEVICE EXAMPLES

A. Magnetofluidic Magnetometer

We have developed a functional magnetofluidic, in-fibre

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magnetometer, based on a ferrofluidic Fabry-Perot, defected Bragg grating, incribed in the grape-fruit shape MOF [7]. By adopting here the photonic design presented in reference [7], the ferrofluidic defect scanning the MOF Bragg reflector, can be translated by magnetic fields, allowing direct correlation of the spectral changes with the local magnetic flux density (see upper part of Fig.1). This MOF optofluidic magnetic field probe was interrogated in reflection mode using a 50/50 fibre coupler, either a broadband source or a fibre pigtailed laser diode and an optical spectrum analyzer. We found that by changing the type of the ferrofluid used (by means of viscosity), in conjunction with the Bragg grating strength and length this magnetometer exhibits different sensitivity and dynamic range (see lower part of Fig.1); lower viscosity ferrofluids (EFH1) of the same/similar magnetisation exhibit better sensitivities.

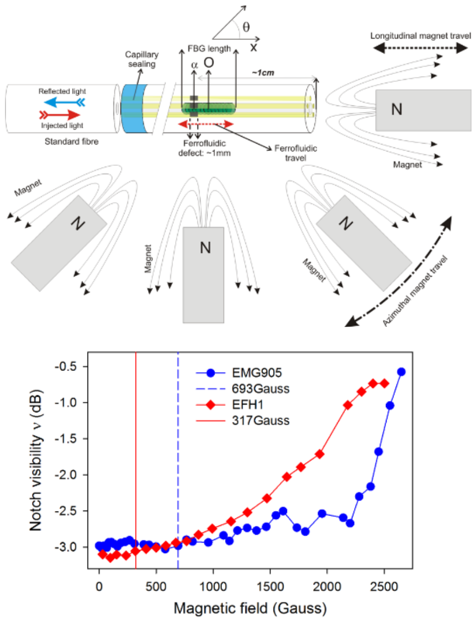

Fig. 1(upper) Schematic of the ferrofluid infiltrated MOF-Bragg grating magnetometer. (lower) Notch visibility v changes due to the movement of the ferrofluidic defect into the MOF Bragg grating versus the magnetic field applied along the fibre axis, for two different ferrofluids infiltrated. Vertical lines denote the measurement sensitivity threshold for each device realized.

The magnetometer wass capable of measuring DC magnetic fields from 317 to 2500Gauss, upon ferrofluid used; AC magnetic fields up to 12Hz were also probed using the same device. This device also exhibited capabilities of directional measurement of the magnetic field [7].

B. Magnetoviscosity magnetometer

In another example a polymer MOF was infiltrated with diluted EMG905 ferrofluid, while exploiting magnetoviscosity effects induced [6]. The sensing principle of this probe is based on the effect of the magnetic field on the transmission loss properties of the infiltrated ferrofluid, affecting wavelengths near its absorption tail band. The short wavelength cut-off absorption band of the ferrofluid undergoes large spectral red-shifts under magnetic field excitation. These short wavelength spectral changes of the infiltrated ferrofluid are interrogated through the hosting polymer MOF, changing its transmission function. Experimental and simulation studies performed [6] shown also that the sensing behaviour is also underlined by a magnetorefractive index component that affects the confinement losses of the fibre. Further experimental studies illustrated that the ferrofluid infiltrated inside the polymer MOF undergoes significant scattering loss changes when magnetic stimulus is applied; these scattering losses are more prominent near the short wavelengths cut-off of the infiltrated fibre.

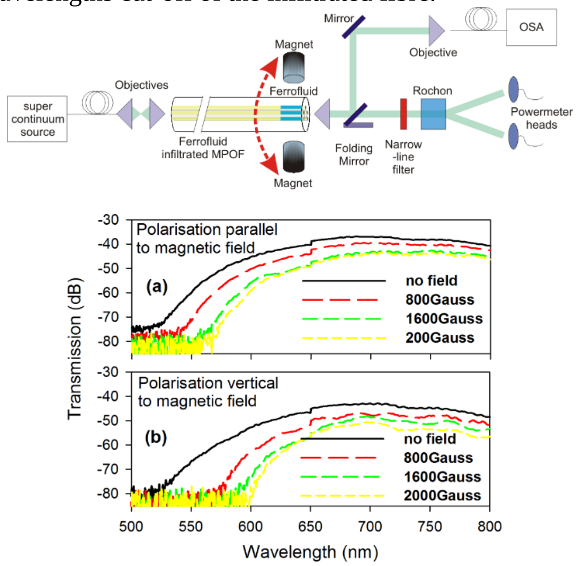

Fig. 2 (upper) Schematic of the experimental set-up for characterising the magnetoviscosity polymer fibre probe. The output signal from the MPOF can follow two different paths by employing a folding mirror: the upper path is used for spectral analysis with the help of an OSA, while the lower path is used for polarization resolved measurements at a specific wavelength. (lower) Polarisation resolved transmission spectra of the 1cm ferrofluid infiltrated MPOF for different magnetic field strengths, measured using the set-up presented in the upper part of Fig.2.

Using the experimental set-up presented in the upper part of Fig.2, by placing a polarizer after the collecting objective lens, and keeping the magnetic field at a fixed azimuthal state, the spectra of the lower part of Fig.2 were measured, for polarizations of light parallel and vertical to the magnetic field direction. These spectral measurements shown that the polarization vertical to the magnetic field lines suffered greater transmission losses compared to the parallel one (~6.8dB). This also affects the short band shifts of the vertical polarization which were also substantially greater. This magnetoviscosity based probe measured magnetic field fluxes from 200Gauss up to 2000Gauss, with significant polarisation sensitivity that allowed the measurement of the azimuthal direction of the magnetic field with respect to the MOF axis.

C. Fiber outcladding magnetosensitive devices

Tilted Bragg and long period gratings inscribed in standard optical fibres, for inducing strong cladding mode resonances of narrow- or broad-band nature, were also immersed in ferrofluids for developing magnetic field sensors and actuators. Tilted fibre Bragg gratings forming Fabry-Perot cavities between the core and cladding area of standard optical fibres, result in distinct and spectrally modulated ghost modes observed at short wavelengths with respect to the Bragg wavelength [16].

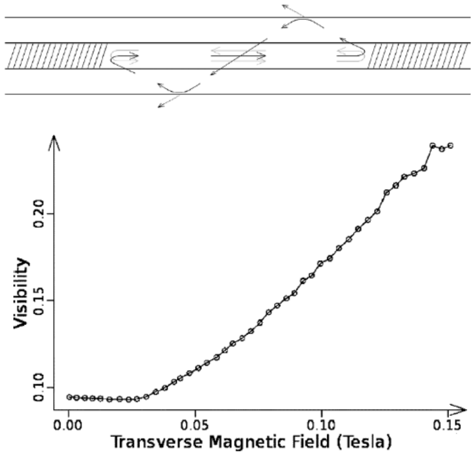

Fig. 3 (upper) Design of the cladding ring sensor showing propagation for the Fabry–Pérot (Bragg) and ring (ghost mode) resonances. (lower) Visibility of fringes response to an applied static transverse magnetic field.

These ghost modes of tilted Fabry-Perot Bragg gratings immersed in ferrofluids undergo modulation strength changes when magnetic field is applied; these spectral modulation changes are quantified using Fast-Fourier transformations with respect to the magnetic field applied. Using this optical configuration magnetic field fluxes up to 1500Gauss were measured with a sensitivity of 25Gauss; the tilted Fabry-Perot Bragg gratings also offer the possibility of athermal measurements.

Devices of similar operation were also realised utilising long period gratings (LPGs) for forming actuators [23]; that was achieved using ferrofluids of tailored refractive index [24] as fluidic outcladdings [15]. In such a scheme the ferrofluidic outcladding is translated along the LPG length via a static magnetic field resulting in alterations of the spatial overlap of the outcladding ferrofluidic medium with the LPG perturbation; namely, the transmission spectrum of the optical fibre is modified with respect to the ferrofluid position.

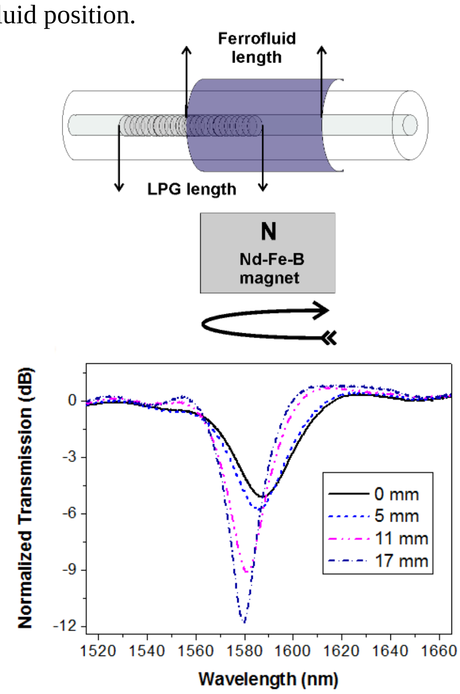

Fig. 4 (upper) Schematics of a ferrofluidic long period grating actuator. (lower) Transmission spectrum of an LPG overlaid with a ferrofluidic socket tranlated at different positions along its length.

Changes in the extinction ratio of the LPG greater than 6.5dB were measured for a LPG of 16mm length, and a ferrofluidic outcladding socket of the same length.

IV. SUMMARY

Device examples of optical fibre magnetic field probes and actuators utilising ferrofluids as transducing sensing elements were illustrated; while employing PCFs, MOFs and standard step index optical fibres as hosting platforms. On-going investigations include the implementation of ferrofluids and other magnetosensitive fluids into multi-core MOFs and the combination of ferrofluids with whispering gallery mode cavities for realising high sensitivity magnetometers.

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