MAGNETIC-FIELD FIBER OPTIC SENSORS USING MAGNETIC NANOFLUIDS

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1. Introduction

The traditional optical fibers are now broadly applied as sensors for measurement of many physical quantities like mechanical stress, pressure, twist, temperature, electric and magnetic field and others [1]. These quantities can be measured locally or as distributed in space [2]. So we can distinguish the local fibre optic sensors (FOS) or space distributed FOS. The practical applications of these sensors are permanently growing mainly due to the high level parameters and rather low realization cost as compared with other types of sensors [3]. Special group of these sensors concerns the measurement of the magnetic field (MF). At present many approaches to the solution and design of FO MF sensors do exist [1, 4]. The basic principle of MF FOS consists in the influencing of the effective refractive index in the core or in the cladding of the sensing OF and in the detection of that influence by the measurement of various parameters such as transmission loss, interference dip shifting and several others. One of the significant approaches how to use the OF for the MF sensing is the use of the suitable fluids with dispersed magnetic nanoparticles [5]. The magnetic fluids (MFL) when coming into contact with the fibre significantly change the electrodynamic properties of core and the cladding modes. The induced changes by external MF can be detected by various approaches. In this contribution we bring some of latest trends in the utilization of standard OF in combination with magnetic fluids for the design of the MF FOS.

2. MFS based on use of the integrated FO-Michelson interferometer with MFL

The OF Michelson interferometer (MI) with several centimetres length can be easily fabricated in an SMF by a CO_2 laser with good reproducibility. The advantages of OF MI with MFL can be exploited to fabricate an alternative MF sensor with small size and relatively high sensitivity. The MI is shown schematically in Fig. 1 where a micro notch elaborated by a laser pulse is located on an SMF. When the light beam propagating in the SMF reaches the air notch, the mode-field diameter of the fundamental core mode is enlarged and part of light is coupled to the cladding of SMF. The cladding modes are excited due to mode-field mismatch. As a result the input optical beam is split into two optical paths at the notch along the core and the cladding of the SMF, respectively. After transmitting a distance L it is then reflected by the end facet of the fiber. The two reflected optical beams recombine and interfere at the notch leading to regular interference fringe with relatively high contrast. The air notch is the key of the structure in which the cladding modes are expected to be excited and the excited modes can further propagate in the SMF. Fundamental mode LP_{01} propagating mainly in the fiber core is coupled to the cladding at the notch position. After the deformation region (notch) the mode-field radius in the Y direction sharply increases but that in the X direction remains nearly the same. Therefore one can expect that the excited cladding modes caused by the asymmetric structure are the LP_{1m} modes which are different from the symmetrical LP_{0m} mode caused by the tapered input fiber [6].

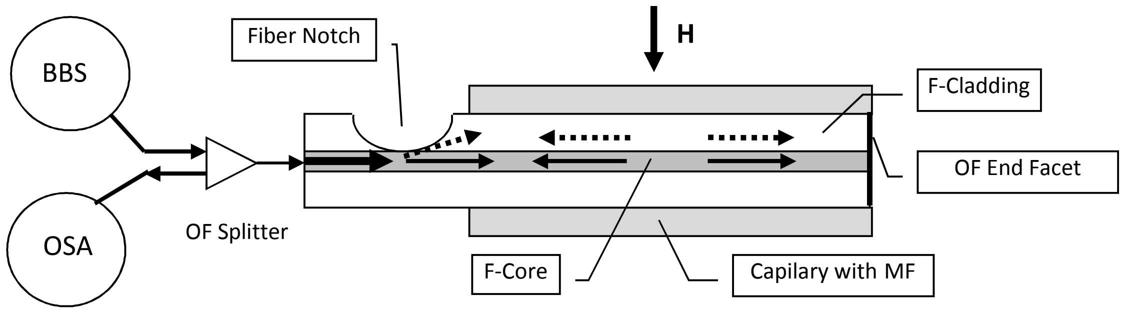

Fig. 1 *Schematic diagram of the in-fiber MI based on the notch in SMF.*

For the structure mentioned before the fundamental mode LP_{01} is coupled to the asymmetric LP_{1m} mode at the micro notch with length of cca 100 µm. Moreover, the depth of the micro notch also affects the characteristics of the fundamental mode. As the notch depth increases, the fundamental mode energy declines. The fringe visibility of the MI can be calculated as $V=(I_{co}-I_{cl})/(I_{co}+I_{cl})$. Therefore a reasonable choice of the deformation depth is essential for excellent sensor production.

According to the above description the core and cladding paths constitute the arms of the MI whose reflective spectrum can be mathematically described by $I= I_{co}+I_{cl,m}+2.(I_{co}I_{cl,m})^{0,5}.\cos(\Phi_m)$ and $\Phi_m =(4\pi\Delta n^m_{eff}L)/\lambda)$, where I_{co} and $I_{cl,m}$ are the intensities of the core mode and the m-th asymmetric cladding mode respectively. Δn^m_{eff} is the effective RI difference between the core mode and the m-th asymmetric cladding mode, L is the physical length of the MI and λ is the input wavelength in vacuum. Φ_m is the phase difference between the core mode and the m_{th} asymmetric cladding mode. According to the above relation the intensity of the interference signal reaches its minimum value (I_{min}) when Φ_m becomes an odd times number of π. In this case, the centre wavelength of the interference valley of the n_{th} order is $\lambda n = (4\pi\Delta n_{meff}L)/[(2n+1)\pi]$. If the RI surrounding the fiber increases, the effective RI of the asymmetric cladding mode increases by δn^m_{eff} , while the effective RI of the core mode stays almost constant. So Δn^m_{eff} decreases by δn^m_{eff}. *Therefore the center wavelength of the interference valley of the n_{th} order shifts to the shorter wavelength by $\delta\lambda_n$. $\delta\lambda_n \approx 4\delta n_{meff}L/(2n+1)$.* It is clear that the interferometer can be used to monitor the environmental RI change by measuring the wavelength shift of $\delta\lambda_n$.

The scheme of the described MF sensor is shown in Fig. 2. It is based on a *MI with the MFL acting as the modified cladding.* An in-line optical fiber MI with interference length of 20 mm is first inserted into a 15 mm length glass capillary with an inner diameter of 1.0 mm. Then the capillary is filled-in with a MFL to form a MFL cladding layer outside the interference arm. Two ends of the capillary are sealed with UV glue to prevent the MFL from leaking out. The external MF is applied perpendicularly to the sensor in the region where the MF is uniform [7]. The characteristic dependence between the wavelength shift and the variation of the MF strength is shown in Fig. 2.

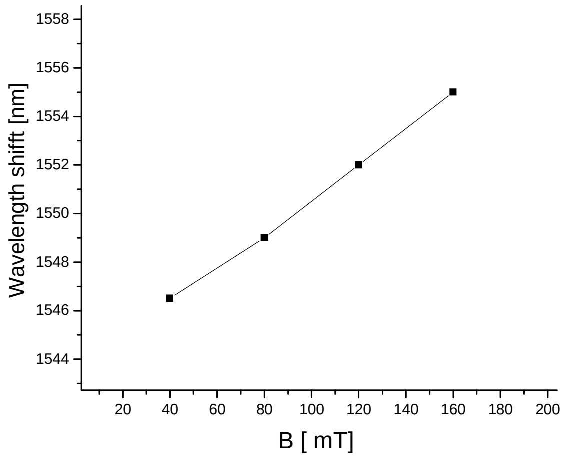

Fig. 2 *The relationship between the wavelength shift and the variation of the MF strength.*

It indicates that the wavelength shift linearly increases with the increment of the MF strength and the sensitivity is up to 64.9 pm⁄mT, which is 20 times higher than that of 125 μm diameter. The sensor's sensitivity and measurement range can be improved by optimizing the magnetic fluid characteristics since the MFL RI is in relation with the surfactant, the solvent, the solute, and their quality [7].
The performance of the described configuration and the experimental results show that the fiber MF sensor with different interference arm diameter has generally different sensitivity. It depends on the MF value which is changing from 0 to 120 mT. The MF sensor with the interference arm's diameter of 50 μm is most sensitive to the external MF and the sensitivity approaches 64.9 pm⁄mT, which is 20 times higher than that achieved with arm diameter 125 μm.

3. MFS based on the use of the S-M-S structure and MFL

Different from the above-mentioned sensing schemes, optical sensors based on "singlemode–multimode–singlemode" (SMS) fiber structure have the advantage of low cost and ease of fabrication [8]. The analysed experimental SMS fiber structure consists of a piece of 12-mm-long MMF whose two ends are spliced to the single mode fibers (SMF). The core and cladding diameters of the MMF are 105 and 125 μm, respectively. The SMS fiber structure is corroded by 10% HF acid for a few tens of minutes to decrease the cladding diameter of the MMF. Experimental samples are obtained by immersing the corroded SMS fiber structures in the MFL. The diameter of the magnetic nanoparticles is around 10 nm. The experimental MFLs have a moderate magnetic nanoparticle concentration (cca 1.87 % in volume fraction).

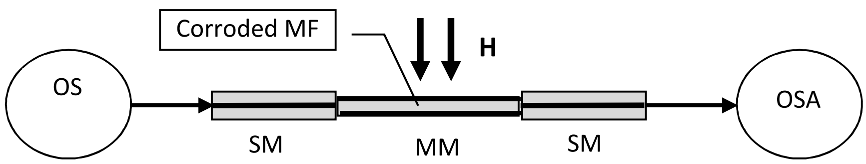

Fig. 3 *The block scheme of the experimental setup for investigation of the S-M-S structure MF sensor*

Light from the broadband optical source OS is coupled into the SMS fiber structure. The transmission spectrum is measured and analyzed by an optical spectrum analyzer OSA, Fig. 3. The resolution of the OSA is 0.01 nm. The sensing structure is placed in a uniform MF with non-uniformity of less than 0.1% in the MMF region. The strength of the MF can be adjusted to the required value. The MF direction is perpendicular to the OF axis. The source light is not polarized so polarization issues are negligible. When light of fundamental mode LP_{01} within the SMF comes to the MMF the high-order modes LP_{0j} are excited within the MMF and interference between these modes occurs. The transmission spectrum is monitored with the OSA and can be described as [9]

$$I(\lambda) = \sum_{(i,N)} \eta_i^2 . I_0(\lambda) + \sum_{i \neq j} \eta_i . \eta_j \cdot I_0(\lambda) \cdot \cos(2\pi \Delta_n L / \lambda), \quad (1)$$

here I_o is the intensity of the fundamental mode LP_{01} in the SMF and N is the total number of excited modes in the MMF. η_i and η_j are the coupling coefficients of the LP_{0i} and the LP_{0j} mode, respectively. Δn is the difference between the effective RI of the two modes and L is the length of the MMF. *The effective RIs of different modes will change differently when the RI outside the MMF varies. It will result in the variation of transmission spectrum according to Eq. (1).* As MFLs have unique MF-dependent properties of RI they can be used as the cladding of the corroded SMS fiber structures to sense the MF. According to Eq. (1), the visibility of the interference dip is maximal when the intensities of the involved modes are equal. The SMS fiber structures are corroded for 1620, 1650, and 1680 s. The exact values of the wavelength dips are obtained through fitting the experimental transmission spectra to Eq. (1). *Herein the relative shift is defined as the shift of the dip wavelength under a certain MF with respect to that under (120x80) A/m*. For the long-time corroded MMF more evanescent field outside the fiber can be influenced by the MF. This will lead to a greater shift of the transmission spectrum under the same MF strength. The sensitivity of the spectrum-shift-based magnetic sensor is defined as $d\lambda/dH$, where λ is the dip wavelength of the spectrum. Fig. 4 indicates that the dip wavelength varies almost linearly with the external MF strength at low field regime [H < (325x80) A/m]. By linear fitting of the experimental data in the almost linear regions the sensitivities

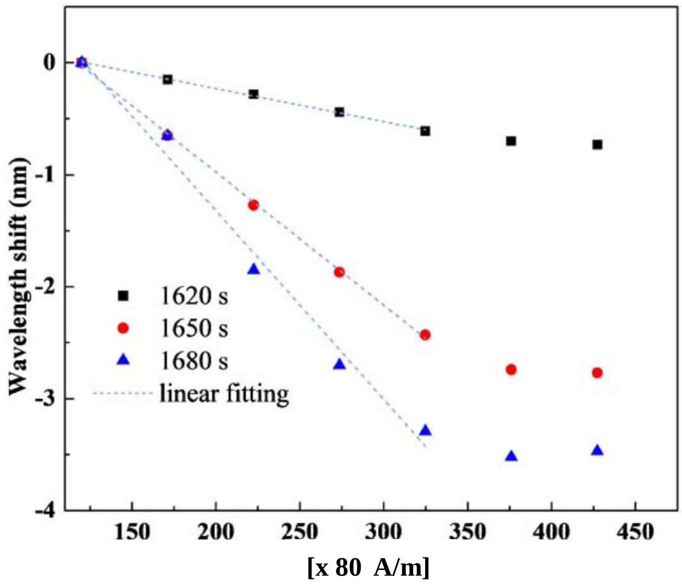

Fig. 4 *Wavelength shift as a function of the magnetic field strength for SMS fiber structures corroded for different times.*

of sensing system are obtained to be (−2.95, −11.88, and −16.86)/80 pm⁄(A/m), corresponding to the structures corroded for (1620, 1652, and 1680) s, respectively. Taking the 1680 s corroded SMS fiber structure as an example the sensitivity of the proposed magnetic field sensor is 7 times higher than that using a MFL as the cladding of the PCF (~2.367/80) pm⁄(A/m) [9] and more than twice larger than that based on a microfiber MI (~6,49/80 pm⁄(A/m) [10]. The sensitivity of the experimental structure (corroded for 1680 s) used for magnetic field sensing can reach (−16.86/80) pm⁄(A/m). The interference dip may not be distinguishable if the SMS fiber structure is corroded for a very long time. The optimum corrosion time is 1620 s. The proposed sensor is cost effective. The technique may possess the potential of being applied to several promising applications.

4. Conclusion

Due to high sensitivity, measurement range and relatively small dimensions and also low realization cost as compared with traditional sensors FOS are growing rapidly worldwide. Also the MF FOS utilizing standard OF with special shape modifications and in combination with the interacting MFL are very attractive and a significant effort to their analysis and design is devoted. We have brought a brief analysis and summary description of two special approaches to the solution of the MF OFS based on the use of:

1. SMF with a notch in the cladding which splits the principal mode field in the core into two parts – one remaining in the core and the other penetrating into the cladding and in such a way creating two arms of the MI. End reflected back propagating modes along the core and the cladding which is exposed to the influence of MFL, interfere at the notch again and the wavelength shift of the interference minimum in the reflection spectrum is measured as a function of the external MF. Sensitivity of cca 64,9 pm/mT can be achieved by this approach.
2. SMS structure where the MMF section is exposed to the external MFL and the wavelength shift of the minimum in transmission spectrum of the sensor is measured as a function of the external MF. The measurement sensitivity of cca (16,89/80) pm/(A/m) was achieved. The sensitivity strongly depends on the MMF diameter.

Finally – both above described approaches can be further optimized by adjusting of several parameters of the particular structure. There is a lot of possibilities for further perfection of this kind of MF FOS mainly by the tuning of MFL composition, by optimization of the geometrical parameters of OF used and also tby the inventing and finding of new structures and basic ideas.

Acknowledgement

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