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# Fiber-Optic Interferometric Sensor of Magnetic Field for Structural Health Monitoring

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**Abstract**

In this paper we report on results of measurement of AC and DC magnetic field by fiber-optic interferometric sensor. Principle of operation is based on change of length of optical path cavity between the magnetostrictive wire and fiber-optic tip. Any change of the outside magnetic field causes elongation or contraction of the sensing wire. Using a fiber-optic sensing configuration based on single-mode 3x3 coupler and low-coherence interferometry we were able to read the instant separation between the wire and fiber ends with accuracy of about 50nm. This separation corresponds with the intensity of the magnetic field in the range of 50nT to 800μT what is measured by using well calibrated magnetometer. The sensor is dedicated for on-line structural health monitoring of composite materials made of carbon reinforced epoxy matrix with integrated magnetic particles. Due to final purpose to be embedded in the structure, the sensor is designed to have small overall size of about 250μm in outside diameter.



Keywords: fiber-optic sensors; magnetic field; interferometry

## 1. Introduction

There is a strong effort in the scientific and engineering community to predict the behavior of the material structure by structural health monitoring (SHM). Numerous techniques are in use today for structural health monitoring (SHM): acoustic emission system, acousto-ultrasonic system, phased array, fiber-optics [1]. Fiber-optic sensing techniques generally have a numerous advantages for SHM due to well-known features of optical fibers: EMI resistance, small overall dimensions, ability to be embedded without disturbing of the domicile matrix etc. Nowadays, there is in use different fiber-optic sensing techniques such as: intensity modulated, Fabry-Perot interferometers, optical time domain reflectometry (OTDR), fiber Bragg gratings (FBG) [2,3].

Probably the most frequently used for monitoring of composite structure based on carbon or glass fiber reinforced polymers (CFRP, GFRP) is FBG technique [3]. However, the main problem in FBG sensors is a strong influence of the parasitic signals mainly caused by temperature effect which is often for an order of magnitude higher than useful signal caused by strain in the structure. In this paper we propose relatively simple technique based

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on low coherence interferometry performed in "all-in-fiber" sensing configuration, made of single mode optical fiber.

## 2. Principle of Operation

The interferometric detection configuration, depicted in Fig. 1a is basically a Michelson type, made of a 3x3 singlemode fiber optic directional coupler. It is composed of three inlet and three outlet arms made of single mode fiber having core diameter of 9 µm and cladding diameter of 125 µm for 1300nm. The arms are connected with a fused 3×3 coupler that serves for mixing and combining of the input and back reflected light beams. Details in Fig.1a show what is going on with light beams coming out from the fibers. In both arms we have the first reflection from the tip of the fiber and this is so called Fresnel reflection with about 4% of back reflected intensity. The rest of the optical power impinged the target (magnetostrictive wire end) and mirror and again reflects back getting in the fiber. Such signals recombine in the coupler and further in the two outlet arms connected with two photodiodes. Very important property of the coupler is generation of the phase shift between the two interference signals for $2\pi/3$ that provides so called quadrature signal processing [4]. The main advantage is avoiding the signal fading and providing the useful signal during the entire measuring procedure. Actually, while a signal captured by one photodiode going to diminish the other signal increasing and vice versa. Due to optical phase difference (OPD) in the sensing and reference arm, occurs interference between the light beams in these arms. The interference signal has been captured by two photodiodes. A specific future of the white light interference is periodicity of the signal having a form of the coherence function of the light source. Usually this is Gaussian function and because of that the interferometric packet has a bell shape.

After scanning procedure we obtain a characteristic coupling delay curve shown in Fig. 1b with two distinct interferograms superimposed upon the curve. The first interferogram occurs due to the interference between the light beams back reflected from the tip of the sensing fiber and scanning mirror. This interferogram is static and usually larger then the next one. The second interferogram occurs due to the interference between the light beam back reflected from the target and scanning mirror. This interferogram is movable and reflects the position of the target. Hence, the target position ($\Delta D$) depends on the influence of intensity of the external magnetic field H(T) and can be determined by measuring the separation from the central position of the two interferograms. This is exactly the principle how we are going to measure the DC and AC magnetic field. Being the first interferogram is always present in the captured signal it means that we can determine the absolute position of the target. This property makes a significant advantage of this technique versus commonly used high coherence laser interferometry technique. An additional advantage of this technique is ability to provide absolute measurement of distance even in the case when the signal is loosed due to various reasons, e.g. switching off the power supply.

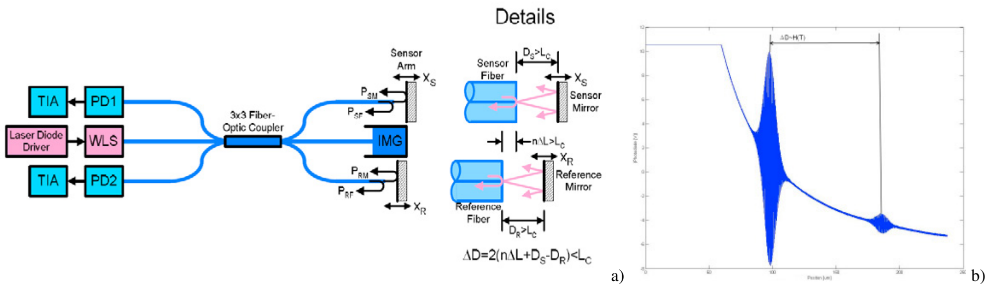


Fig. 1. a) 3×3 fiber-optic interferometric scheme; TIA-transimpendance amplifier, PD1 and PD2-photodiodes, WLS-white light source, Pi-various optical powers, $D_S$ and $D_R$ –sensor and reference mirror positions, n-index of refraction of fiber core, $L_C$-coherence length of the light source, $\Delta L$-length difference between the sensing and reference arm. b) Coupling curve captured by the one photodiode during the scanning procedure. The first interferogram (left side) comes due to interference between the sensing fiber tip and reference mirror and second (right side) due to interference between the target/magnetostrictive wire tip (sensor mirror) and reference mirror.

### 3. Experiment

In Fig. 2 we schematically present experimental set up for measurement of magnetic field intensity based on “all-in-fiber” sensing configuration described above.

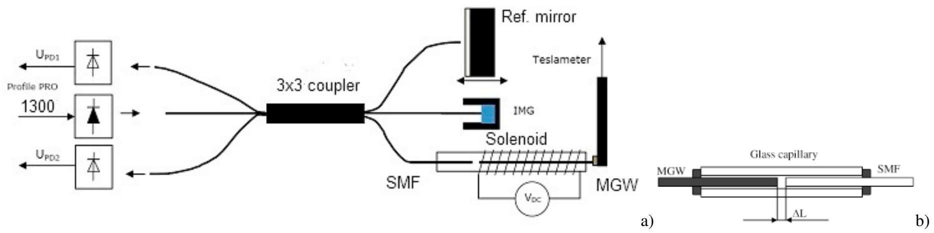


Fig. 2. a) Experimental set-up. Magnetic field has been changed by change of the current through the solenoid. B) The sensing gage is put together with well calibrated magnetometer for parallel measurement. SMF-singlemode fiber, MGW-magnetostrictive wire

The basic concept of the design is magnetostrictive wire (Metallglas Fe77,7/B15/Si7,5; Goodfellow) of 150µm in diameter and 100mm in length as a movable mirror in the sensing arm of an interferometer. Against the polished wire end is the end of the sensing fiber and both of them are aligned in the glass capillary forming the miniature sensor gage of 250µm in diameter presented in Fig. 2b. The original separation between the two of them is about 80-100µm and changes in dependence on intensity of the outside magnetic field in the range of 50nT to 800µT as can be seen in Fig. 1b. This separation can be read remotely with accuracy of about 50nm using the reference arm of the interferometer by scanning the position of the wire end, by reference mirror or by monitoring of photodiode signals. Magnetic field has been generated by solenoid and the intensity has been measured by Teslameter 6010 produced by Bell Co in the range of 0,1µT to 30T with accuracy of +0,25% in DC and +1% in AC mode.

### 4. Results and discussion

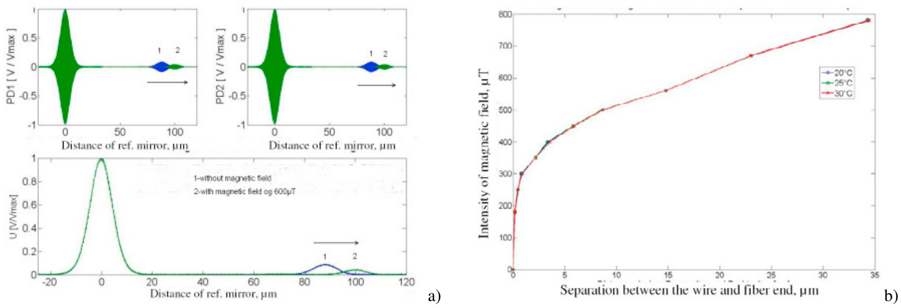


Fig. 3. a) Normalized photodiode signals of PD1 and PD2 (above) and calculated quadrture signal (lower) with Gaussian envelopes over the first (large and static) and second (small and movable) interferometric patterns b) Change of separation between the wire and fiber end in dependence on DC level of magnetic field for the three different temperatures

In Fig. 3 we present the change of separation between the polished end of the magnetostrictive wire in dependence on DC level of magnetic field for the three different temperatures of 20, 25 and 30$^{o}$C. After signal processing depicted in Fig. 3a we could see the movement of the second pattern from an initial position (1) to position (2) when magnetic field of 600µT is applied. This shift, denoted by arrow, is caused by contraction of the sensing wire. The polished end of the wire moves back from the sensing fiber causing an increase of the gap. It is obvious in Fig. 4b. We didn’t see any influence of various temperatures on the shape of the curve. In the range from

400 to 800μT the sensor has liner dependence with sensitivity of about 16μT/μm. That corresponds with an ultimate sensitivity of 0,8μT since the accuracy of determination of maximum of Gaussian function is about 50nm.

In Fig. 4 we present the results of measurement of AC change of magnetic field at 2kHz measured by fiber-optic sensor. On the left side above of Fig. 4a we show raw photodiode signal captured during the AC change of the magnetic field. Below this diagram is filtered signal in a short time frame just to show the interferometric pattern. After FFT applied on the filtered signal we obtained spectrum of the signal (right side of Fig. 4a) with clear peak at 2kHz. The height of the peak corresponds with intensity of amplitude of AC magnetic field of 50nT while in Fig. 4b we show the result after 150nT. Signal-to-noise ratio for the first case is about 12 while for the latter is 30dB.

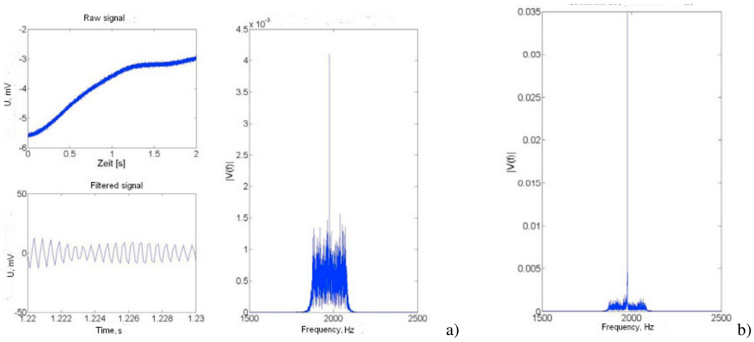


Fig. 4. a) Raw and filtered photodiode signals and FFT of the same signal after AC alternation of magnetic field of amplitude of 50nT and b) 150nT at 2kHz

## 5. Conclusion

We present a fiber-optic sensor of magnetic field aimed for structural health monitoring of composite materials with integrated magnetic nanoparticles. Basic principle is low-coherence interferometry used for on-line measuring of extension and contraction of magnetostrictive wire during AC and DC alternation of external magnetic field. We found an overall sensitivity of the sensor of about 0,8μT of amplitude of the DC and better than 50nT of amplitude of the AC change of magnetic field in the range of 0 to 800μT.


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