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Miniature magneto-optic angular position sensor

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This Letter describes a miniature Fabry–Perot, contactless, magneto-optic sensor for angular position measurement. The sensor utilizes a magneto-optic fluid comprising barium hexaferrite nanoplatelets that become birefringent in the presence of an external magnetic field and a compact fiber-optic sensor system for tracking the liquid's optical axis direction. An efficient temperature compensation system is provided which allows the use of otherwise highly temperature-sensitive magneto-optic liquids. An unambiguous measurement range of 90° and a resolution of better than 0.05° are demonstrated experimentally.

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The angular/rotary position is a fundamental mechanical parameter that is measured in a wide variety of systems. Arguably, after temperature, the rotary position is the second most common physical quantity measured in industrial systems [1,2]. To accommodate this wide variety of rotation-sensing needs, different electrical sensor approaches have been established in the field of rotary position sensing, including resistive, inductive, capacitive, Hall-effect, electro-optical, and other sensors [1]. However, electrical designs are sensitive to electromagnetic interference and chemically harsh environments, they cannot be operated easily in remote locations, and they suffer from different operating limitations. Also, genuinely miniature versions are possible with only a restricted number of these electrical designs. None of the above conventional methods allow for fully electrical passive/dielectric and remote rotary-position sensing. Optical rotary-position sensors which utilize optical fibers to connect the measurement location and the sensor are, thus, of significant interest. Fully optical approaches can fulfill the requirements regarding electrical passivity, the possibility of remote operation, and harsh environment compatibility. However, most of the reported fiber-optic principles [3,4] do not provide the possibility of contactless operation, which is an essential requirement in most modern angular/rotary-position sensors, as it provides high reliability and a long operating lifetime of the sensor.

In this Letter, we present a contactless, miniature, all-optical angular position sensor. The position sensing is achieved by sensing the optical axis spatial orientation (direction) in a

magneto-optic fluid which is made birefringent by an external permanent magnet that revolves around the sensor. The application of magnetic fluids has been considered before in various sensing applications [5–7], mainly for sensing in magnetic fields [8–16]; however, their implementation in rotation sensing seems to be difficult.

The proposed sensor is shown in Fig. 1(a) and consists of a miniature container with a magneto-optic fluid, a pair of permanent magnets connected to a rotating body or part that revolves around the container, and a fiber-optic sensing system which can determine the direction of fluid's optical axis. The magnetic field generated by the magnet pair orientates nanoplatelets within the fluid and thereby induces birefringence within the fluid. The optical axis of the magneto-optic fluid is, thus, parallel to the direction of the magnetic field. The fiber-optic sensing system for the determination of the spatial orientation of the liquid's optical axis further contains a fiber-coupled microcell, an interconnecting lead-in polarization-maintaining (PM) optical fiber, and an optical signal interrogation system.

The microcell comprised a biconical ceramic ferrule with a diced slit, a lead-in PM fiber on one side, and a coreless fiber on the other side. The lead-in PM fiber was sputtered with a 370-nm-thick layer of TiO₂, which yielded 4% reflectance. The coreless fiber was first sputtered with a 375-nm-thick aluminum layer, thus achieving a reflectance of about 90%, and afterwards sputtered with a 100 nm SiO₂ layer to protect the aluminum mirror from direct exposure to the magnetic fluid. The lead-in fiber and the coreless fiber were inserted into the ceramic ferrule at a mutual distance of 500 μm and fixed with an epoxy (Epo-Tek 353ND). Both sputtered fiber ends thus defined the magneto-optic-liquid-filled, in-line, low-finesse Fabry–Perot interferometer (FPI). The produced microcell was further inserted into a tapered glass tube at the tapered end. The tube was filled with magnetic fluid and sealed by a silicon sealant (the glass tube/container inner and outer diameters were 7.3 and 6.0 mm, respectively). The tapered section of the glass tube provided alignment of the lead-in fiber and microcell into the center of the glass tube. The fabricated sensor, packed in the glass tube/container with added magneto-optic fluid, is presented in Fig. 1(b). Good mechanical stability of the proposed sensor was provided by applying a fabrication method employing a ceramic ferrule and a high-strength, temperature-stable epoxy. The ferrule guarantees accurate alignment of both fibers, even in the presence of external vibrations. The current

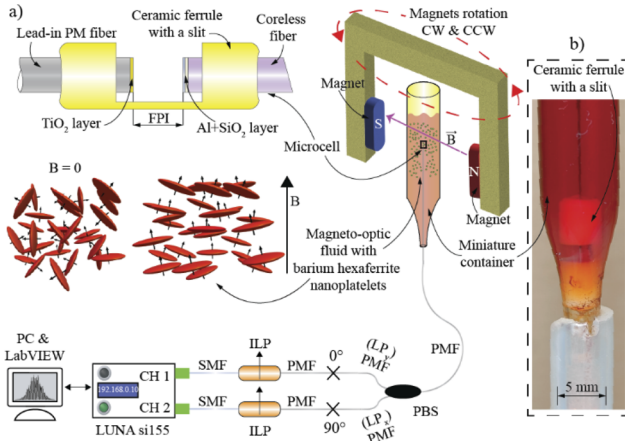


Fig. 1. (a) Sensor setup and the microcell design and (b) the fabricated sensor with housing submerged in the magneto-optic fluid.

sensor design also encapsulates the ferrule with mounted fibers into a sealed glass tube, which provides a mechanically robust assembly and thus eliminates special packing requirements in most applications. Furthermore, the glass tube encapsulating the ferrule and liquid could be replaced by a nonmagnetic, corrosion-resistant metal tube to further increase the mechanical robustness of the sensor. The presented designs could be directly applicable in a broad range of industrial rotation-sensing applications. The structure was placed in the center between the permanent magnets that revolved around the glass tube. The magnets had dimensions of 25×10 mm, were separated by a 25-mm-wide air gap, and generated a nearly homogeneous magnetic field with a density of 35 mT. The magnets were fixed to a fork-like holder which allowed free rotation around its central axis, as shown in Fig. 1 (see Visualization 1). The magneto-optic fluid is composed of ferrimagnetic barium hexaferrite nanoplatelets stabilized colloiddally with dodecylbenzenesulfonic acid in 1-butanol [17]. The nanoplatelets are made of a birefringent material with an optical axis parallel to the platelet axis. In the absence of a magnetic field, the platelets are oriented randomly, so the birefringence averages out. In the presence of a field, the platelets, on average, orient with the optical axis along the field and the suspension becomes birefringent. Important properties, for example, the birefringence and magneto-optic response, originate from the specific magnetocrystalline structure of the nanoplatelets; specifically, from the orientation of their magnetic easy axis (90°) perpendicular to the nanoplatelets' basal plane [18,19]. The saturated magnetization of the nanoplatelets was $36 \text{ Am}^2/\text{kg}$. The original suspension with 20 mg/ml of nanoplatelets was diluted with 1-butanol in the volume ratio 1:8.

The optical signal interrogation and processing was accomplished by the application of a depolarized multichannel spectral interrogator (LUNA si155), which was connected to a personal computer (PC) running the LabView development environment. The outputs of the two interrogator channels were connected to fiber linear polarizers (ILPs) to provide fully linearly polarized light at the output of the signal interrogator, as shown in Fig. 1. These fibers, with linearly polarized outputs, were then connected to a polarizing beam splitter/combiner (PBS) while rotating the axis of the fiber coming from the second interrogator channel by 90° . The PBS thus combined the light from both

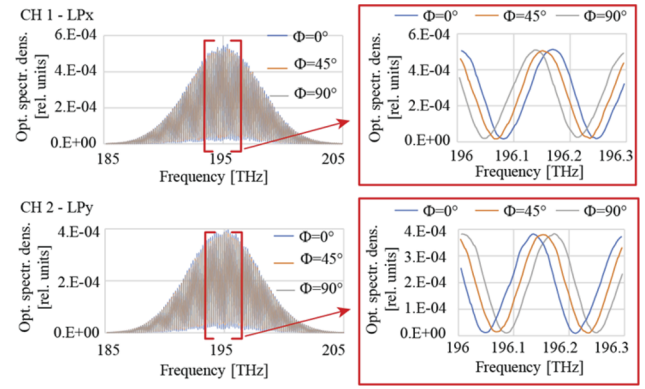


Fig. 2. Gaussian-windowed, back-reflected optical spectrum readouts from both channels at three different angular positions of the magnets: $\Phi = 0^\circ$, 45° , and 90° .

channels into a single fiber such that the light from the first channel was coupled to the slow axis of the coupler's output PM fiber while the light from the second channel was coupled to the fast axis of the same fiber. Since the interrogator provides independent and cross-talk-insensitive readout of individual channels, this configuration allows for independent reading out of the microcell's (FPI) optical path lengths while using orthogonal linear polarization states. The readout of the first channel thus allowed the determination of the fluid's refractive index (RI) when the E-field of the probe light was parallel with the slow axis of the lead-in PM fiber, while the readout of the second channel yielded the liquid's RI for the case where the E-field of the probe light was parallel with the fast axis of the lead-in PM fiber. Figure 2 presents typical Gaussian-windowed, back-reflected optical spectrum readout from both channels (LPx and LPy) when changing the angular position of the magnets to 0° , 45° , and 90° . The optical path length changes of the microcell were determined by recording and signal processing the back-reflected optical spectrum using inverse Fourier transformation (IFFT). In this procedure, IFFT is performed on the acquired spectrum, and then the phase of the IFFT component with the peak absolute value is calculated. Further division of the calculated phase component by $2\pi L$ (L is the length of the microcell) yields the RI change of the medium within the microcell. The procedure is described in detail, for example, in Refs. [20,21], and provides a robust, low-noise RI variation readout which is immune to the multipath interference that can occur due to multiple reflections in any sensor setup.

Since the optical axis follows the magnetic field vector orientation, a full revolution of the magnets around the microcell generates sinusoidal changes in the RIs measured along the fast (LPx) and the slow (LPy) axes at the output of the lead-in PM fiber:

$$n_{LPx} = n_0 + \frac{1}{2} \Delta n_b \cos 2\Phi, \quad (1)$$

$$n_{LPy} = n_0 - \frac{1}{2} \Delta n_b \cos 2\Phi, \quad (2)$$

where Φ represents the rotational position of the magnets with respect to the slow axis of the lead-in PM fiber, n_0 is related to the RI of the fluid n_{liq} when no external magnetic field is present ($n_0 \approx n_{liq} + 1/6 \Delta n_b$), while Δn_b represents the fluid's birefringence. In principle, by measuring n_{LPx} and n_{LPy} , and by knowing n_0 , the above expressions provide the possibility to directly determine the rotation angle Φ . There is, however, difficulty with

the determination of n_0 due to the liquid's high temperature sensitivity, which is of the order of a few times $10^{-4}/\text{K}$ RIU. Under practical operating conditions, where the temperature operating range exceeds at least a few tens of degrees K, the temperature-induced change of n_0 would be within the 10^{-3} RIU range, thus far exceeding Δn_b , which is of the order of 9×10^{-3} RIU (as shown later in the discussion of our experimental work). A properly temperature-compensated demodulation scheme is required to eliminate this hindering temperature influence. On the other hand, the fluid's birefringence Δn_b is related to the physical rotation of the nanoplatelets in the magneto-optic fluid, and is almost constant over a broader temperature range when using constant and sufficient magnetization, which aligns most of the nanoplatelets and brings the fluid close to saturation. Therefore, Δn_b can be measured at the given magnetic field density produced by external magnets (for example, by the calibration procedure when the magnets undergo one full turn around the sensor and the maximum change in RI is measured, as explained further in detail below). When Δn_b is known, Φ can be determined independently from n_0 by subtracting the RIs measured along both lead-in fiber axes:

$$n_{LPx} - n_{LPy} = \Delta n_b \cos 2\Phi. \quad (3)$$

From the above expressions, Φ can be expressed as:

$$\Phi = \frac{1}{2} \left(\arccos \left(\frac{n_{LPx} - n_{LPy}}{\Delta n_b} \right) \right). \quad (4)$$

Subtracting the RI values measured along the fast and the slow axes thus eliminates n_0 fully from the equations related to Φ , which is otherwise the main source of temperature dependence in Eqs. (1) and (2).

Figure 3(a) shows the measured raw phases (obtained using the FFT algorithm) and calculated RI changes (as measured directly by the interrogation system) along both polarization axes versus the rotational position of the magnets when performing two full 360° rotations of the magnets around the sensor (this test was performed within about 20 s at room conditions

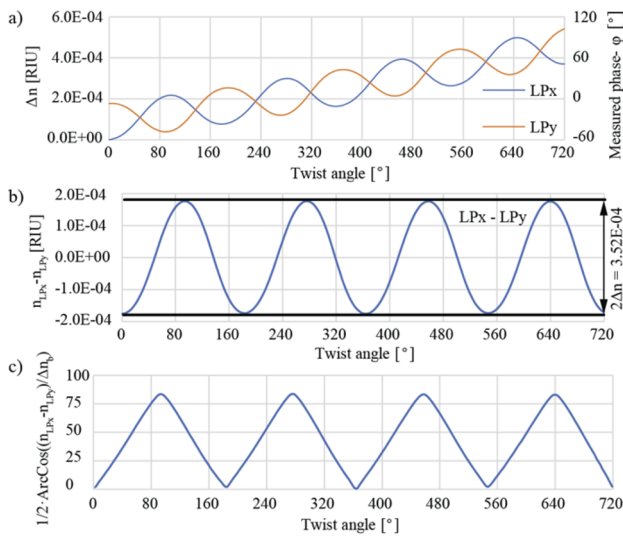


Fig. 3. (a) Measured phase (obtained using the FFT algorithm) and calculated relative RI changes for both polarization axes/channels. (b) Measured RI difference between both polarization axes/channels. (c) Calculated angular position Φ of the magnets (see Visualization 1).

at 22°C , so the temperature can be assumed to be nearly constant; it drifts within about 200 mK of 22°C). The measured RI changes follow two raised sine periods delayed by 180° , with a magnitude of about 2.2×10^{-4} RIU (this magnitude also corresponds to the fluid's birefringence at the given density of the magnetic field). Figure 3(b) shows the difference between the measured RI changes shown in Fig. 3(a). The calculated difference oscillates sinusoidally around a value of nearly zero, with the amplitude corresponding to the fluid's birefringence. Two initial self-calibrations were performed before applying Eq. (4) for the calculation of the magnet's angular position Φ . Firstly, for a given density of the magnetic field generated by the magnet pair used (35 mT in our case), Δn_b was determined experimentally by rotating the external magnet pair around the sensor axis for several turns while measuring and recording n_{LPx} and n_{LPy} . The difference between n_{LPx} and n_{LPy} was then calculated as shown in Fig. 4(b). The peak-to-peak values of the recorded $n_{LPx} - n_{LPy}$ difference were determined and averaged further. The difference between the average minimum and maximum recorded values of $n_{LPx} - n_{LPy}$ thus corresponded to $2\Delta n_b$, as also indicated by Eq. (3). One half of the difference between the minimum and maximum recorded values of $n_{LPx} - n_{LPy}$ was thus used as Δn_b in the further calculation of Φ . Secondly, the mean value of the RI difference was offset slightly from zero in our experimental setup (by a value of the order of 0.5% of the peak value or RI difference). This offset was probably caused by asymmetry in the interrogator's channel readout system and the limited polarization extinction ratio that can be achieved in the proposed PM fiber readout system. This offset was not temperature dependent, and was subtracted from the measured RI difference. It should be stressed, however, that the mitigation of this initial offset requires good parallelism of the microcells' optical end surfaces. We tested several microcell designs before reaching the solution described in Fig. 1. Nonparallelism of both surfaces that formed the FP interferometer proved to be the dominant cause of temperature-dependent initial offsets, which easily exceeded 1% of the peak RI difference value. Therefore, all cleaved fibers used to build the microcell were checked interferometrically before reflective layer deposition and assembling the microcells.

Figure 3(c) shows Φ calculated from the measured RI using Eq. (4). The latter indicates a linear correlation between the rotation angle and system output, with a 90° unambiguous measurement range.

To investigate the temperature stability of the proposed system further, we enclosed the entire sensor (including the magnets) within a compact container, which allowed for controlled temperature variation of the sensor and magnets while reading the sensor. Figure 4 shows an example of the measured RI change when rotating the magnets around the sensor continuously while inducing an ambient temperature change of about 25 K. A significant effect of temperature on the measured RI is apparent which exceeds the magnetic-field-induced RI changes by about two orders of magnitude. Figure 4(b), which shows the difference in measured RI between both polarization channels, however, indicates that both channels subtract highly efficiently over the given temperature range and yield a sinusoidal, rotation-dependent signal with a constant (almost temperature-independent) amplitude and a stable offset of nearly zero.

Thus, despite the strong temperature impact on the absolute value of the fluid's RI, the RI difference between both measurement polarization channels remains well defined and depends

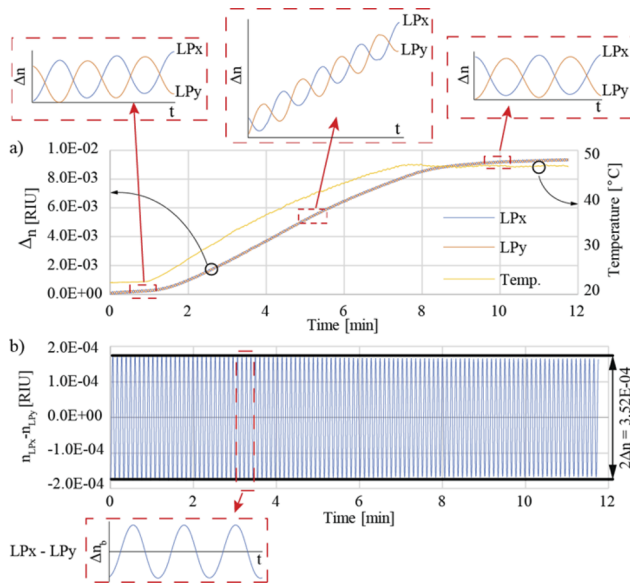


Fig. 4. (a) Measurements of relative RI along both polarization axes when changing the temperature by 25 K and rotating the magnets continuously. (b) Difference between both RI measurements.

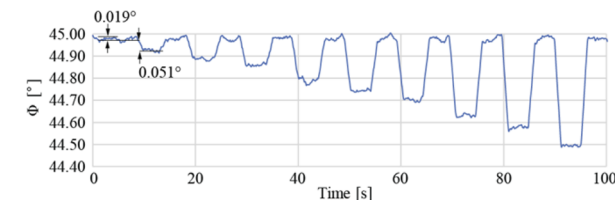


Fig. 5. Demonstration of the sensor's resolution: left and right movements of the rotational stage from 0.05° to 0.45° in 0.05° steps.

only on the rotation angle. This highly efficient subtraction is a consequence of using a single compact microcell design which performs RI measurements along both orthogonal polarization axes within the very same volume of the liquid sample.

The angular displacement resolution was estimated by placing the magnets at $\Phi = 0^\circ$ and performing small (0.05°) steps in both the clockwise and counterclockwise directions. The results are shown in Fig. 5, and indicate an angular resolution of better than 0.051° , most likely around 0.02° . This test was performed at a sampling frequency of 1 Hz.

In conclusion, this paper has presented a miniature, contactless angular displacement sensor operated through an optical fiber. The system utilizes a small amount (1 ml) of magneto-optic fluid, which becomes birefringent in the presence of the

magnetic field, and a compact fiber-optic system to read out the spatial orientation of the fluid's optical axis. The large impact of temperature on the raw measurement results, which originates from the fluid's high temperature sensitivity, was successfully eliminated from the measurement results by the application of a highly symmetrical differential configuration and compact optical system setup, which measured the fluid's RI within the same volume of the liquid. The proposed optical configuration canceled out the large RI variations of the fluid efficiently while extracting the useful rotation-related RI changes required to determine the angular position of the external magnet.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this Letter are not publicly available at this time, but may be obtained from the authors upon reasonable request.

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