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Continuous-wave fiber cavity ring-down magnetic field sensing method based on frequency-shifted interferometry

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Received July 4, 2014; accepted October 11, 2014; posted online November 20, 2014

We demonstrate a novel all-fiber cavity ring-down (CRD) magnetic field sensing method that uses frequency-shifted interferometry, and does not require any optical pulse and fast electronics compared with conventional CRD schemes. The sensing element in the ring-down cavity is a fiber taper surrounded by magnetic fluid, whose refractive index varies as an external magnetic field is applied. Magnetic field strength measurement is successfully achieved within a range from 8 to 850 Gs. A resolution of 0.00105 ± 0.00003 dB/Gs is obtained in the approximately linear segment from 423.2 to 766.6 Gs. The sensing method is potential for sensing other physical and chemical parameters.

OCIS codes: 060.2370, 060.4370, 070.4340, 160.4670.

doi: 10.3788/COL201412.120604.

Ever since conventional cavity ring-down (CRD) techniques were first proposed in 1984 by Anderson et al.[9], who used CRD techniques to measure mirror reflectivity, CRD has been developed to be a sensitive and powerful technique to detect weak optical losses[2–4]. Unlike conventional direct measurement schemes in which the attenuation of transmitted light through a sample is measured, CRD techniques measure the ringdown time of the cavity instead of the intensity decrease with absorption length and concentration. The absorption loss introduced by a sample in the CRD cavity can be derived from the measured CRD time[9]. The higher the absorption, the shorter is the CRD time. Proportional to the loss in the cavity, the ring-down time is independent of excitation intensity, and this results in a low susceptibility to laser noise and immunity to external loss contributions. As a result, the signal to noise ratio of CRD is enhanced[6,7]. The attenuation coefficient of the absorption sample can be derived. However, pulsed light that is usually generated by modulation of a continuous-wave (CW) laser used in CRD requires a narrow linewidth and a high-speed detector. To avoid utilizing pulsed light, CW light as the source in a frequency-shifted interferometry (FSI) CRD technique proposed by Qian et al.[8,9], this technique is different from phase-shifted (PS) CRD[10] and time domain CRD[5,6]. In PS-CRD, an intensity modulation is applied to the input light so as to produce a phase shift related to the temporal decay time constant[11], whereas in FSI-CRD, frequency modulation produces an interferogram which contains light intensity decay information as a function of the distance traveled. A Fourier transform (FT) is carried out to obtain the familiar temporal decay curves. In time domain CRD, light intensity decay information is closely related to real-time signal. Only by recording CRD time, the cavity loss can be obtained. However, in FSI-CRD, the cavity loss was only revealed from the FT of the frequency-modulated CW interference signal exiting from a ring-down cavity. The deduction of cavity loss in FSI-CRD is equal to processing the relationship between the intensity decay and the distance traveled by light. A cavity optomechanical magnetometer based on a magnetostrictive material and an optical microresonator was proposed by Forstner et al. and a sensitivity of 400 nT Hz\(^{−1/2}\) was achieved[22]. A magnetic field sensor configured as a core-cladding-mode interferometer by incorporating magnetic fluid (MF) was proposed and the sensitivity reached ~16.206 pm/Gs ranging from 0 to 214 Gs[23]. If sensing elements, such as long-period gratings[14] or fiber tapers[15,16], are inserted in the cavity, as customary in the conventional CRD techniques, many physical or chemical quantities[17,18] that affect the intensity of the light inside the FSI-CRD cavity can be detected by this method.

In this letter, we report a novel magnetic field sensing method based on FSI-CRD with a CW source, a high-gain balanced photodetector, an acousto-optic modulator (AOM), and a data acquisition card (DAQ). The magnetic field sensing method is verified by experiments with the use of a type of MF as the sensing material inside the fiber CRD cavity. The tunable refractive index characteristics of MF, as a kind of the

1671-7694/2014/120604(5) 120604-1 © 2014 Chinese Optics Letters
sensitive medium\(^{[19-21]}\), are applied in this letter. The results show that this novel method based on FSI can be applicable for detecting current and magnetic field intensities. As a result, a stable relationship between cavity loss and magnetic field ranging from 8 to 850 Gs is obtained.

The FSI technique was proposed by Qian et al., and its comprehensive description was provided in Refs. \([8,9]\); the technique is similar to a frequency-shifted fiber Signac loop. As shown in Fig. 1\(^{[8]}\), CW light with a frequency \(\nu\) separates into two beams after traveling across the coupler \(C_1\). One beam in path \(l_1\) is frequency shifted by an amount of \(+f\) after it passes through a frequency shifter, and the other beam in path \(l_2\) will oscillate with its original frequency \(\nu\). The two components continue to propagate into the cavity through couplers \(C_2\) and \(C_3\), respectively, and then circulate in the ring-down cavity. After each trip in the cavity, one fraction of the modes propagating in clockwise and anticlockwise directions leaks out of the cavity and reaches the coupler \(C_1\). They may interfere if they arrive at the same time after they have traveled the same number of round trips in the cavity. The leaked mode fraction in the clockwise direction is also frequency shifted by an amount of \(+f\) while it passes through the frequency shifter. Therefore, the two fractions of light have the same frequency \(\nu+f\) (Table 1). Because field components \(E_{2m}\) are shifted earlier than \(E_{1m}\), the two fractions of light interfere at coupler \(C_1\) and show a phase difference \(\Delta\varphi^{[8,9]}\), whereas the coherence length of the light source is shorter than the fiber cavity length \(d\). The detailed transmission path is shown in Table 1, where \(m\) is the number of light round trips in the cavity, and \(d = l_1 + l_2(-53m)\) is the cavity length.

\[
\Delta\varphi = 2\pi \frac{n\left[l_1 + l_2 + m(l_3 + l_4) + l_5 - l_6\right]}{c} f. \tag{1}
\]

The differential output signal \(\Delta f^{[8,9,22]}\) (shown in Eq. (1)) is a cosine function of \(f\), and this cosine function oscillates at a frequency \(F_m = n(md + l)/c\) related to both the distance \(L = md\) in the ring-down cavity and the asymmetry of two arms of the Mach–Zehnder interferometer: \(l = l_1 + l_2 + l_5 - l_6\).

\[
\Delta I \approx \sum_{m=0}^{\infty} I_m \cos\left(\Delta\varphi\right) = \sum_{m=0}^{\infty} I_m \cos\left[2\pi \frac{n(md + l)}{c} f\right] = \sum_{m=0}^{\infty} I_m \cos\left(2\pi F_m f\right). \tag{2}
\]

In Eq. (1), \(n\) is the effective mode index of the fiber, \(c\) is the speed of light, \(l_1\) is the fiber cavity length defined in Fig. 1. \(I_m\) is the amplitude proportional to the interfering light intensity after \(m\) cavity round trips, and each cosine component corresponds to the interference of the light that has traveled through the fiber cavity for \(m\) round trips.

We take the FT of \(\Delta I\) to resolve the distance that the light has traveled in the cavity from the oscillation frequency components \(F_m\). \(F_m\) is unique for each round-trip number \(m\) and is equally spaced by \(nd/c\). A series of \(I_m^{[8,9,22]}\) exponentially decreases as light passes the sensing element in the cavity. If the attenuation coefficients are recorded in different magnetic fields, we can deduce the cavity loss. Therefore

\[
I_m = I' \exp\left[-(a - \log\kappa) m\right] = I' \exp\left[-(a - \log\kappa) \frac{L}{d}\right], \tag{3}
\]

\[
\delta_{\text{loss}} = 4.34a = 4.34\left(\frac{d}{l_1} + \log\kappa_e\right), \tag{4}
\]

where \(\kappa_e\) is the loss inherent to the cavity setup, which includes the background cavity loss of an empty ring-down cavity, splices loss, fiber scattering loss, fiber absorption loss in the cavity sections \(l_2\) and \(l_3\), fiber couplers insertion loss of \(C_2\) and \(C_3\), and attenuator loss. \(l_1\) is the attenuation coefficient of exponential function. \(a\) is the sensing element transmission attenuation, which depends on the refractive index of the MF\(^{[19-21]}\) because of evanescent field absorption. Since the effect

**Table 1. Field Components Arriving at \(C_1\) After Round Trips in the Ring-down Cavity**

<table>
<thead>
<tr>
<th>Field Components</th>
<th>Path Followed</th>
<th>Frequency upon Returning to (C_1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{1m})</td>
<td>(C_1 \rightarrow l_1 \rightarrow l_2 + md \rightarrow C_3 \rightarrow l_5 \rightarrow AOM \rightarrow l_6 \rightarrow C_1)</td>
<td>(\nu+f)</td>
</tr>
<tr>
<td>(E_{2m})</td>
<td>(C_1 \rightarrow AOM \rightarrow l_4 \rightarrow C_3 \rightarrow l_2 + md \rightarrow l_1 \rightarrow C_1)</td>
<td>(\nu+f)</td>
</tr>
</tbody>
</table>
of temperature to MF refractive index is weak\cite{19}, we ignore the impact of the temperature in our experiment.

The experimental system is shown in Fig. 2. A superluminescent light-emitting diode source (44 nm bandwidth with a central wavelength of 1550 nm) was set to 5 mW at 1550 nm, and the light separated into two components at C1 after it passed through the circulator (its three direction ports are shown in Fig. 2). The differential interference voltage signal was digitized by a 100 Ks\textsuperscript{-1}, 16-bit USB multi-channel DAQ card (USB-6361 National Instruments, Austin, TX, USA), which was triggered by AOM for synchronization. A custom LabVIEW program was used to control the AOM (AMM-100-20-25-1550-2FP BRIMROSE) linearly sweeping from 90 to 110 MHz at step of 0.01 MHz with a 1 ms duration and fitted the peaks of the intensity signal. The fitting results were averaged and stored for further processing. A high-gain balanced photodetector (New Focus 2117, 10 MHz bandwidth, >10\textsuperscript{7} V/W gain) was used to attain photoelectric conversion, with a gain of 34.78 dB. The linear polarization states of the two interfering beams fluctuated due to the polarization drift\cite{23}. Two linear polarization controllers (three pads) were used to maintain a preferable interference phenomenon. Due to pressure, strain and birefringence would affect the polarization states of the interfering beams and to avoid these disturbances we fixed the ring-down cavity and the sensing device on a hover platform. In addition, a stable and favorable environment would enhance the accuracy of measurement and the sensitivity of the sensor.

We prepared a section of 30 mm long SMF-28 fiber and etched it in the hydrofluoric acid solution at the concentration of 25\% for approximately 2.5 h. The fiber taper (18 µm diameter) was then immersed in MF (EMG Series Water-based Ferrofluid, Ferrotec, USA), which was composed of Fe\textsubscript{3}O\textsubscript{4} nanoparticles, water soluble dispersant, and water with volume 3.2\%, 17.6\%, and 79.2\%, respectively. The effective refractive index of MF varied with the change in magnetic field strength since Fe\textsubscript{3}O\textsubscript{4} particles in the MF agglomerated and formed a long-chain structure parallel to the field direction with the increment of magnetic field strength\cite{20–21}. To obtain the quantitative information between the refractive index of the MF and magnetic field intensity, the method reported in Ref. \cite{24} was employed and the results are shown in Fig. 3. The inset shows the measured reflected powers $P_{mf}$ in real time for various magnetic field strengths when the detecting fiber tip was placed in air and immersed in water, respectively. The central wavelength of the ASE light used was 1310 nm and the working temperature was 27 °C. From Fig. 3, it can be seen that the refractive index increased monotonously from 1.3830 to 1.4037 as the field strength rose from 300 to 750 Gs, and then it almost remained unchanged as the field strength was more than 800 Gs.

Therefore, the intensity of light that passed through the sensing element decreased as a result of evanescent field absorption. The cylindrically symmetrical magnetic field was changed by adjusting the passing current through a pair of coaxial ferromagnetic coils, and

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{Refractive index $n_{mf}$ as a function of magnetic field. The inset shows the measured reflected powers $P_{mf}$ in real time for various magnetic field strengths.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Typical fiber CRD transient measured by FSI-CRD system at a current of 0.35 A. The inset is the raw interferogram of the measurement.}
\end{figure}
trend of the cavity loss is almost consistent with the features of MF refractive index under magnetic field in Fig. 3. Because the measured data are obtained in different principles and experimental setups, there is a slight difference between the linear range in Fig. 3 and that of in Fig. 6. The real-time change of cavity loss with the increase in current can be clearly observed from the rising steps in the inset of Fig. 6.

In conclusion, we establish a FSI-CRD magnetic field sensing method. The FSI technique is used to transfer the distance traveled by the continuous lightwave into the frequency domain by the FT. The results are not affected by the intensity fluctuation of the CW light. Optical pulses and high-speed detections as in conventional CRD system are therefore avoided. The cavity loss can be deduced from the rate of decay in the amplitude–frequency curve. The sensing method is verified by experiments with the use of a type of MF as the sensing material inside the fiber CRD. A stable relationship between cavity loss and magnetic field is shown from 0 to 850 Gs. The experimental results achieve a resolution of \(0.00105 \pm 0.00003\) dB/Gs in the approximately linear segment from 423.2 to 766.6 Gs. Therefore, this sensing method indicates a promising potential for other physical or chemical sensing if other kinds of optical fiber sensing elements are employed inside the fiber CRD.

This work was supported by the Project of National Science Foundation of China (Nos. 61077061 and 61377091) and the Fundamental Research Funds for the Central Universities (Nos. WUT 2013-II-023 and WUT 2014-zy-115).

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1.0 1.05 1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Field (Gs)</td>
<td>8 72 131 190 249 306 364 423 481 540 598 657 718 767 833 888 942 1000 1059 1116 1179 1247 1301</td>
</tr>
</tbody>
</table>

Table 2. Relationship Between Current and Magnetic Field Beside the Sensor
References