Magnetic field interaction with guided light for detection of an active gaseous medium within an optical fiber

Florian V. Englich,1,* Michal Grabka,2 David G. Lancaster,1 and Tanya M. Monro1

1Institute for Photonics and Advanced Sensing (IPAS) and School of Chemistry and Physics, The University of Adelaide, SA 5005, Australia
2Center for Magneto-Optical Research, Department of Photonics, Institute of Physics, Jagiellonian University, 30-059 Kraków, Poland
*florian.englich@adelaide.edu.au

Abstract: We report a novel fiber-optic sensing architecture for the detection of paramagnetic gases. By interacting a modulated magnetic field with guided light within a microstructured optical fiber, it is possible to exploit Faraday Rotation Spectroscopy (FRS) within unprecedentedly small sample volumes. This approach, which utilizes magnetic circular birefringence and magnetic circular dichroism effects, is applied to a photonic bandgap fiber to detect molecular oxygen and operates at a wavelength of 762.309 nm. The optical fiber sensor has a 4.2 nL detection volume and 14.8 cm long sensing region. The observed FRS spectra are compared with a theoretical model that provides a first understanding of guided-mode FRS signals. This FRS guided-wave sensor offers the prospect of new compact sensing schemes.

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References and links
1. Introduction

Gas sensors based on microstructured optical fibers (MOFs) offer a number of advantages compared to free-space gas sensing architectures. They can provide long optical pathlengths since the guided light can interact with the gas sample along the fiber length. For example, hollow-core photonic bandgap fibers (HC-PCFs) serve as an efficient platform for interacting light with absorbing gas molecules [1,2], and have also been used to enhance nonlinear-optical effects through high power densities of the guided light [3]. MOFs enable the use of extremely small (nL) sample volumes, compared to tens of mL necessary for single or double-pass absorption cells, and hundreds of mL for conventional multi-pass cells. Their small dimensions, mechanical flexibility, and ability to be integrated with standard optical fiber components offer strong sensor miniaturization potential for applications in confined spaces and harsh environments. Free-space spectroscopic techniques such as cavity ringdown spectroscopy (CRDS) have already started to successfully transition into optical fiber-based sensing architectures, as demonstrated by fiber-loop ringdown spectroscopy, therefore utilizing small sample volumes [4,5].

The use of magneto-optical effects in optical fibers is an area of increasing interest. Recent work includes the development of magnetic field sensors [6], enhancement of the Faraday Effect in doped fibers [7], and microstructured magneto-optical fibers for the development of fiber-based optical isolators and circulators [8]. Here we report, to the best of our knowledge, the first demonstration of Faraday Rotation Spectroscopy (FRS) within microstructured optical fibers. To date FRS has only been implemented in free-space, bulk-optic sensor systems. We demonstrate a fiber-optic FRS architecture by employing a HC-PCF as a miniature gas cell filled with a magneto-optical active gaseous medium, specifically molecular oxygen (O₂). Oxygen was chosen as it plays an important role in industrial, environmental and atmospheric sensing applications. In this work we investigate the interaction of an externally applied, modulated magnetic field with the guided light, and explore how the fiber waveguide properties influence and can be exploited to manipulate the FRS signal behavior. The observed FRS spectra are compared with a developed theoretical model to provide a first understanding of these guided-mode FRS signals.

2. Faraday rotation spectroscopy

Faraday Rotation Spectroscopy (FRS) is a highly sensitive and selective, background-free, spectroscopic technique that exploits the magneto-optic Faraday rotation effect to detect paramagnetic trace gases such as nitric oxide (NO) [9,10], molecular oxygen (O₂) [11], or free radical species like hydroxyl radicals (OH) [12]. In FRS, background absorption interference from common diamagnetic atmospheric species such as water (H₂O), carbon dioxide (CO₂) and other non-paramagnetic molecules are eliminated. As described in [9–12], FRS probes the change in the state of polarization of a linearly polarized laser beam as it propagates through a gas cell containing paramagnetic molecules exposed to an external magnetic field. When the laser frequency is in resonance with a Zeeman-split absorption line of the paramagnetic molecular species, magnetic circular birefringence (MC-birefringence) and magnetic circular dichroism (MC-dichroism) are observed. MC-birefringence results from a difference in refractive index for right-handed (RHCP) and left-handed (LHCP) circular polarized light. The originally linearly polarized laser light, which can be considered...
as a superposition of RHCP and LHCP, experiences a rotation of its polarization axis when propagating through the gaseous medium inside the longitudinal magnetic field due to the phase difference experienced between the two circularly polarized components.

Thus the MC-birefringence signal is the difference between the dispersion profiles as depicted in Fig. 1(a), whereas the refractive index difference is proportional to the concentration of the absorbing species. MC-dichroism, as shown in Fig. 1(b), occurs when there is a difference in absorption between the two circular polarized components in the gaseous medium, which changes linear polarized light to elliptical polarized light. Every FRS signal is comprised of both MC-birefringence and MC-dichroism components; their relative strength depends on the individual system and measurement parameters.

3. Experimental setup

In this work we have chosen the \(^{16}\text{O}_2\) transition (A-band) at 762.309 nm (13118.04 cm\(^{-1}\)) \[13,14\] to record FRS signals. This low total angular momentum quantum number transition \((J = 1)\) of molecular oxygen has the advantage of offering relatively strong Faraday rotation signals for low intensity magnetic fields \[11\]. Our MOF-based FRS sensor is depicted in Fig. 2(a). A wavelength-tunable, external cavity diode laser (ECDL) from New Focus (Model: TLB-6712-P-D) with ~20 mW continuous-wave output power, specified <200 kHz linewidth and stable axis of polarization was used to probe the magneto-optical effects inside the HC-PCF. The linearly polarized laser beam was directed to the MOF gas cell, passing on through a Glan-Thompson polarizer (extinction ratio: 10\(^{-6}\)) to ensure the purity of polarization, followed by a half wave plate to set its polarization axis. To couple the laser beam into the pure-silica HC-PC fiber (NKT Photonics AIR-6-800, core dia. ~6 \(\mu\)m, attenuation <0.4 dB/m at 760-800 nm, NA: ~0.17 at 780 nm), an aspheric \(f = 18.4\) mm lens was used. The 24.6 cm long piece of HC-PCF was placed in a glass capillary tube to mechanically isolate the fiber, with both ends vacuum sealed using end caps to form an evacuable MOF gas cell. The detection volume inside the HC-PCF was calculated at 4.2 nL. Note that each of the gas cell end caps had a dead-volume of 1.29 mL. The capillary tube assembly was placed inside a 14.8 cm long air-core solenoid for axial magnetic field generation. A photograph of the complete MOF gas cell with air-core solenoid including fans for air cooling is shown in Fig. 2(b). For better understanding of the gas cell assembly, Fig. 2(c) depicts a concept drawing of the cell end caps with mounted glass capillary tube but without the air-core solenoid.

For AC operation of the air-core solenoid, a series resistance-inductance-capacitance (RLC) circuit driven by an audio amplifier at a resonant frequency of \(f_m = 1.32\) kHz was constructed. When sine-wave modulated at \(f_m\), an AC magnetic field of 0.148 Tesla\(_{rms}\) with 8.9% homogeneity over its length was measured. After the laser light was coupled out of the fiber, a light transmission of ~76% through the HC-PCF’s air core was measured. The
collimated laser beam passes through a second half wave plate to balance the outputs of the Rochon polarizer (extinction ratio: $10^{-5}$), which splits the laser beam into two perpendicular polarized beams of equal intensity. Each beam was focused onto a balanced silicon photodetector enabling differential detection of the FRS signal for improved sensitivity [15]. For lock-in detection, the FRS signal was demodulated at $f_m$ with its in-phase component maximized and recorded. All FRS spectra reported in this article were acquired by scanning the ECDL’s frequency with 0.59 pm/s across the targeted O2 transition, a lock-in time constant of 100 ms and a measurement time of ~0.5 s per averaged data-point.

The HC-PCF used for our fiber-optic FRS system is not specified as a birefringent fiber. An electron microscope image of its structure is shown in Fig. 2(d), whereas the approximately Gaussian beam profile of the HC-PCF output is depicted in Fig. 2(e). NKT Photonics reports it to have a 50-nm wide photonic bandgap (PBG) centered at approximately 770 nm, placing the targeted O2 transition close to the PBG center, where both polarization modes of the fiber are degenerate [16]. Thus even small perturbations will cause coupling between both polarization modes and depolarization of the light. However, by mounting the fiber inside the glass capillary tube, which isolates it from stress and vibrations, it is possible to reduce this effect. We observed that the HC-PCF exhibited two orthogonally oriented polarization axes and confirmed that the polarization state of the light was preserved if coupled to one polarization axis (the polarization extinction ratio was measured to be $10^{-2}$).
4. Experimental results and theoretical model

A series of FRS experiments were performed to investigate the performance of the fiber-optic based FRS sensor. Figure 3 shows FRS spectra recorded for different light coupling conditions into the HC-PCF, achieved by aligning the laser polarization state to both principle fiber axes in turn.

![Graph showing FRS spectra](image)

**Fig. 3.** Fiber-optic based FRS spectra for the 762.309 nm A-band transition of pure O\textsubscript{2} at gas-sample pressure P = 300.5 mbar (T ~307 K) at different coupling conditions (see insets). Dotted (black) traces show measured FRS spectra in good agreement with the solid (red) traces depicting the corresponding modeling results. Signal-to-noise ratios (SNR) are shown.

Optical misalignment, which increases the coupling of light to the higher order modes, was demonstrated to degrade the resulting FRS signals (i.e., offset levels increased, signal...
amplitudes decreased). By optimizing the coupling to the fiber it was ensured that during measurements most of the optical power was coupled into the fundamental polarization modes of the HC-PCF. Under these conditions the laser beam exiting the fiber core, which has an approximately Gaussian profile (Fig. 2(e)), did not change shape or optical power for different light polarization angles to the HC-PCF.

The FRS spectra depicted in Fig. 3 illustrate the effects taking place within the hollow core of the fiber. Figures 3(a) and 3(e) depict FRS spectra for light coupled to one of the two fiber polarization modes, with their observed signal shapes typical for FRS measurements originating from the MC-birefringence effect. When light is launched equally in both polarization modes (Fig. 3(c)), we observe a 4-fold increase in peak-to-peak signal amplitude, as well as a change in shape compared to exciting only one polarization mode. MC-birefringence alone cannot explain this effect. This suggests that the signal itself originates from the MC-dichroism effect within the fiber and also explains the change of its shape. The resulting signal arises from their superposition and its amplitude cannot be larger compared to the situation when only one polarization mode is excited. For the conditions in Fig. 3(c) we calculated a minimum detectable absorption of $1.9 \times 10^{-6}$ cm$^{-1}$ Hz$^{1/2}$. Figures 3(b) and 3(d) present FRS spectra for transitional coupling situations with MC-dichroism evident but not dominating the MC-birefringence. Thus in these cases the signal shapes and amplitudes are influenced by both effects.

To test this explanation of the experimental results, a theoretical model has been developed. Analysis of the light propagation in complex structures such as HC-PCFs requires Maxwell’s equations to be solved, and this can only be done numerically. However, in our case it is possible to make several approximations that simplify the problem. Under optimal coupling conditions in the experiment most of the laser light was coupled to the fundamental mode and thus higher-order modes can be excluded from the theoretical analysis. Additionally, the refractive index change introduced by the gas is small (calculated to be of the order $10^{-9}$) and does not influence light propagation in the fiber. Therefore, the HC-PCF exhibits two orthogonal linear polarization modes, with the gas adding small MC-birefringence and MC-dichroism effects. For simulations of the light polarization in the fiber, the oxygen filled HC-PCF can be modeled as an elliptically birefringent crystal illuminated by a non-divergent laser beam. Using Jones matrix formalism this is equivalent to a medium with the dielectric matrix expressed as [17]

$$\hat{e} = \varepsilon \begin{pmatrix} 1 + \delta_L & -i\delta_C(\omega) \\ i\delta_C(\omega) & 1 - \delta_L \end{pmatrix}$$

where $\delta_L$ and $\delta_C$ are proportional to the linear and circular birefringences and $\varepsilon$ is related to the average effective refractive indices of the fiber modes (for HC-PCF $\varepsilon = 1$). Linear and circular dichroism can also be included in this formalism if $\delta_L$ and $\delta_C$ are taken to be complex. Here the HC-PCF is not linearly dichroic, and thus $\delta_L$ is real. We expect residual structural birefringence emerging from imperfections in the fiber of the order $10^{-7}$ to $10^{-5}$ [18]. The circular birefringence in our system is relatively small (calculated to be of order $10^{-9}$). For the numerical model, dispersion and absorption near the targeted O$_2$ line at 762.309 nm have been calculated using the Kramers-Kronig relation. All the parameters were taken from the HITRAN database [13,14] and a Voigt-profile was used to model the line shape. Absorption line shape contributions other than Lorentzian shaped pressure broadening and Doppler broadening as described in refs [14,19] are neglected. As result the complex refractive index for molecular oxygen (with magnetic field off) can be expressed as [10]

$$\pi(\omega, \omega_0) = \frac{c^2 N \sigma_0}{\omega_0 \Gamma_D} Z \left\{ \Gamma_D^{-1}(\omega - \omega_0 + i\Gamma_D) \right\}$$

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where \( c \) is the speed of light in vacuum, \( N \) is the number density of molecules, \( S \) is the line-strength, \( \omega_0 \) is the central transition frequency, \( \Gamma_D \) is the Doppler broadening at half-width half-maximum (HWHM), \( \Gamma_P \) is the pressure-broadening at HWHM and \( Z \) is the plasma dispersion function. By changing the magnetic field, \( \omega_0 \) for two circular polarizations are shifted by a factor \( \Delta \omega = g \mu_B B / \hbar \) of where \( B \) is the magnetic field strength, \( \mu_B \) is the Bohr magneton and \( g \) is the Lande factor. This gives rise to the MC-birefringence and MC-dichroism, which are included in \( \delta C \) as 

\[
\delta \omega = \omega_0 (\omega_0 + \Delta \omega) - \pi (\omega_0 - \Delta \omega).
\]

By diagonalizing the matrix in Eq. (1) the modes of the filled fiber and their propagation constants can be found. In this way the fiber can be easily included in the Jones matrix formalism. In the formalism, the medium with a dielectric matrix \( \hat{\epsilon} \) is modeled as the \( \exp \left( ik \sqrt{\hat{\epsilon} z} \right) \) matrix with \( k \) as vacuum wave number and \( z \) propagation distance (note: calculating this matrix exponent function requires diagonalization of \( \hat{\epsilon} \)). For the simulations, all optical elements in the system (wave plates, polarizers, balanced detector, HC-PCF) are modeled using matrix operators. Additionally, a lock-in amplifier has been included in the simulations to reflect the experimental configuration. The modeled signal shapes, depicted as solid (red) traces in Fig. 3, show good agreement with our experimentally measured FRS signals.

The theory of our fiber-optic based FRS system is more complex than conventional free-space FRS systems due to the presence of the linear birefringence of the fiber. The optical fiber provides additional parameters that control shapes of the FRS signals (e.g. different coupling conditions). The dielectric matrix shown as Eq. (1) incorporates these effects. This matrix can be divided into two parts (by separating linear birefringence and MC-birefringence / MC-dichroism) and expressed as in the form

\[
\hat{\epsilon} = \begin{bmatrix} 1 & \delta_L & 0 & 0 \\ 0 & 1 & -i \delta_L & 0 \\ 0 & i \delta_L & 1 & 0 \\ 0 & 0 & i \delta_L & 1 \end{bmatrix}
\]

If the term \( \delta_L \delta_C \) is negligible the fiber-optic based FRS system can be described as a free-space FRS system with an additional wave plate. Then the optical fiber takes the role of a wave plate, with the phase retardance related to the linear birefringence. Thus, as in typical free-space FRS measurements with additional wave plates before the analyzer, the measured fiber-optic FRS signals are superpositions of MC-birefringence and MC-dichroism effects with different amplitudes.

However, care has to be taken when making analogies between fiber-optic and free-space FRS systems. By careful analysis of the dielectric matrix from Eq. (1), differences between these systems may be found. For example, it can be shown that in our case \( |\delta_C| \ll \delta_L \) the eigenvalues and eigenmodes of the matrix from Eq. (1) differ in their dependence on \( \delta_L \) from the free-space system – eigenmodes are linear and eigenvalues are quadratic. This leads to further differences in the signals that are observed. For example, this is shown by the results in Fig. 3, which depict how the evolution of FRS signal shapes and amplitudes depends on the initial light polarization angle \( \phi \). This can be also seen in Fig. 4, which shows the peak-to-peak FRS signal amplitude evolution with changing coupling conditions (i.e., light polarization angle \( \phi \)), showing the sine-dependence while rotating the polarization of the light which is the fiber-space specific effect (note that the photodetector is balanced at all times).

Figure 5 depicts the measured pressure dependence of the peak-to-peak FRS signal amplitude at an AC magnetic field of 0.148 Tesla when coupling equally to both polarization modes of the fiber (Fig. 3(c)). The maximum FRS signal amplitude measured around 300 mbar of gas pressure depends on the used magnetic field strength, resulting in a decrease of signal amplitude at higher pressures due to dominating pressure broadening. We experienced filling-times of <5 min. for reaching pressure equilibrium inside the fiber core.
Fig. 4. Evolution of peak-to-peak FRS signal amplitude depending on coupling condition (i.e., light polarization angle $\varphi$) to the HC-PCF. Coupling to a single polarization mode (see Fig. 3(a,e)) produces a minimum; a maximum occurs when both modes are excited equally (see Fig. 3(c)).

Fig. 5. Peak-to-peak FRS signal amplitude dependence at different gas pressures when coupling to both polarization modes of the HC-PCF. The decrease of signal amplitude at oxygen pressures >306.6 mbar is due to dominating pressure broadening.

5. Summary and conclusion

In summary, we have demonstrated a unique platform for studying the interaction of guided light with an active medium. The unique polarization properties of the interaction platform enable access to a qualitatively new environment for magneto-optical effects. The HC-PCF provides structural linear birefringence, and its hollow core, when filled with an active medium can be used to further alter its polarization properties, such as via the introduction of strongly wavelength-dependent circular birefringence and dichroism. It can be envisioned that by changing the fiber geometry and active medium these properties can be independently tuned. Such complex media may prove useful in fundamental studies of guided light and have strong potential for practical applications, e.g., sensors, as demonstrated here in the form of a novel fiber-optic FRS sensing architecture with ultra-low 4.2 nL detection volume. The experimentally recorded FRS spectra are in good agreement with theoretical modelling and show that in our experimental setup it is possible to measure MC-birefringence and MC-dichroism independently by modifying the coupling conditions. Moreover, in the presented MOF-based FRS architecture it is advantageous to incorporate MC-dichroism rather than MC-birefringence, as we observed a more than 4-fold increase of the signal amplitude for MC-dichroism. We anticipate that by applying polarization maintaining fibers this ratio may be increased further.
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