Review of Fibre-Optic Applications in the Geosciences in British Columbia

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Introduction

The importance of technology in monitoring on the scale of millimetres to tens of kilometres the spatial variability of deformation due to heterogeneity and complex geometry of excavations in the short term and long term is demonstrated by the constant monitoring of the geometry of underground openings in mines, as well as the monitoring and measurement of strain and temperature in boreholes in geothermal and hydrocarbon projects. In recent years, fibre optics has become a more significant and noticeably promising technology for geoscience applications, including in underground rock engineering, geothermal energy, geophysics, and oil and gas. Compared to most conventional monitoring equipment, fibre-optic sensors are robust and geometrically flexible, possess long-term stability, are cost-effective, extend coverage with improved resolution, offer data at a higher sample rate and, above all, can be monitored remotely, which reduces the number of workers required to work underground and enhances the safety of any underground operation.

Discrete and distributed sensors are the two main categories of fibre-optic sensors. The comparison of these two types of fibre-optic sensors is shown in Table 1. By changing the spacing of a diffraction grating in the fibre or in a cavity between two ends of micrometre-scale fibre, discrete sensors respond to strain and temperature.

Distributed fibre-optic sensing is a type of technology that allows for continuous, real-time measurements to be made along the entire length of a fibre-optic cable by detecting changes in temperature, strain and other parameters, using the physical properties of light travelling along the fibre. In distributed sensing, the fibre-optic cable itself is the strain and temperature sensor. Distributed-sensing mechanisms can interrogate Rayleigh, Raman or Brillouin scattering phenomena. Distributed acoustic-sensing (DAS) and distributed temperature-sensing (DTS) systems, among others, enable short-term and long-term monitoring of an object to describe its dynamic behaviour.

In the sections that follow, the theory behind fibre-optic sensors and their applications in the geosciences is demonstrated.

Before this work, no attempt had been made to summarize the application of fibre optics in geoscience projects. This study aims to investigate the potential application of fibre optics to geoscience by reviewing previous applications.

Fibre Bragg Grating-Based Discrete Sensor

Theory

Fibre Bragg gratings (FBGs; FBGS Technologies, GmbH, 2022) are discrete sensors created by exposing a single-mode optical-fibre core laterally to a spatially variable pattern of intense laser light. A periodic spatial variation in light intensity induces a permanent increase in the refractive index of the fibre's core, resulting in a fixed index modulation based on the exposure pattern. This type of fixed index modulation is known as a 'grating'. A small amount of light is reflected at each periodic refraction change. When the grating period is nearly half the wavelength of the input light, all the reflected light signals combine coherently into one major reflection at a specific wavelength. This is known as the 'Bragg condition' and the wavelength at which this reflection takes place is known as the 'Bragg wavelength'. The wavelengths of light signals that are not phase-matched to the Bragg wavelength are generally transparent (Figure 1).

Applications

Sensors of the FBG type have been widely employed as a robust and very effective technology for monitoring structural health. The FBG sensor has several advantages over

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Table 1. Comparison between discrete and distributed fibre-optic sensors.

Sensor type	Discrete sensor	Distributed sensor	
	Fibre Bragg grating	Distributed temperature sensing	Distributed acoustic sensing
Operating principle	Wavelength-modulated (periodic modulation of the refractive index over a short length)	Scattering-based (Raman)	Scattering-based (Rayleigh)
Measurement parameter	Strain Temperature Acceleration Pressure	Temperature	Strain
Measurement type	Single-point or multipoint sensing	Continuous	Continuous
Intensity of backscatter light	High	Low	Low
Spatial resolution	Controlled by the physical spacing of the sensor (increase in the spatial resolution = more expensive sensor)	Depends on the sensitivity of the interrogator unit	Depends on the sensitivity of the interrogator unit
Price	High	Low	Low
Advantages	Can measure multiple parameters simultaneously over short distances	Can provide the profile of temperature change along the whole length of the fibre-optic system	Can provide the profile of temperature change along the whole length of the fibre-optic system
Disadvantages	Strain influences temperature results and vice versa Price of the FBG fibre depends on the number of sensors inside (increase in number of sensors = increase in price of sensors)	Compared to FBG, the measurement requires a longer time and averaging	Compared to FBG, the measurement requires a longer time and averaging

conventional sensors like extensometers, strain gauges and dial gauges, such as its small physical dimensions, light weight, immunity to electromagnetic interference, ease of installation, long-term stability and ability to use multiple wavelengths (Morey et al., 1990; Ferdinand et al., 1997; Cappa et al., 2006; Yin et al., 2008). The geotechnical and mining industries have shown a growing interest in FBG-based sensing systems in recent years and numerous papers have been published on the subject in various fields of study. The monitoring of various geotechnical and structural parameters of crucial importance to mining projects, such as internal temperature variations, pressure changes, deformation changes, vertical settlements and lateral deflections, is typically the focus of researchers (Wang and Gage, 2017; Minardo et al., 2018; Vlachopoulos et al., 2018; Yugay et al., 2020).

In addition to being useful to the mining and geotechnical industries, FBG sensors have been employed in the oil and gas industry, mainly to monitor well integrity during production (Zhong et al., 2007; Johny et al., 2016; Qiao et al., 2017; Zhang et al., 2018; Rong and Qiao, 2019).

These FBG sensors deliver reliable and precise monitoring results that give engineers a reasonable performance assessment, based upon which they may take prompt and efficient action to address possible problems. Several FBG ap-

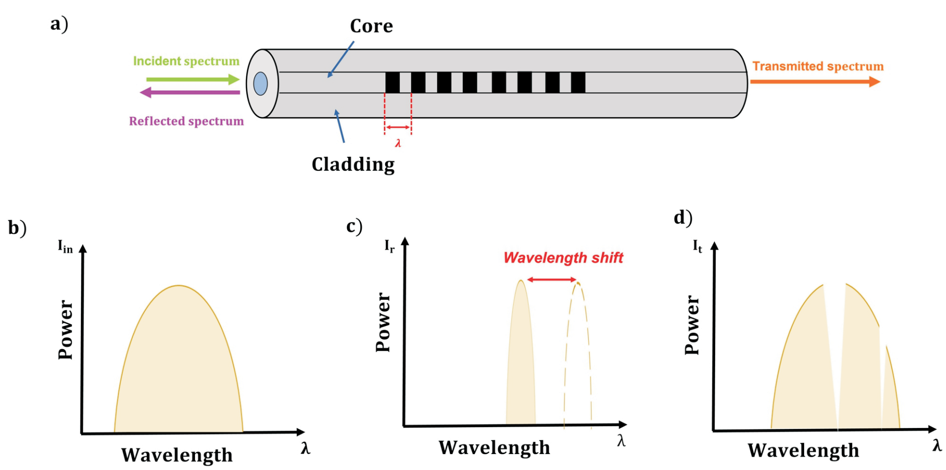

Figure 1. Operating principle of the fibre Bragg grating (FBG) sensor: **a)** the FBG sensor; **b)** incident spectrum; **c)** strained FBG causes wavelength shift and reflected spectrum; **d)** transmitted spectrum (modified from Pendão and Silva, 2022).

plications require additional attention and improvements as they are still in the initial stages of development, such as:

- the use of FBG sensors to directly evaluate the deformability of a rock mass in the field as opposed to the use of indirect classification techniques or extrapolation of laboratory data (Gage et al., 2014);
- the use of FBG sensors in determining the mechanical behaviour of rocks (Tang et al., 2018; Guo et al., 2019);
- the rapid expansion of FBG use and other fibre-optic sensors, particularly in the mining industry, to allow for fully remote real-time monitoring (Zhao et al., 2016; Wang et al., 2021; Hu et al., 2022) and the replacement of mechanical or electrical reference stations, thus making mining operations safer and reducing human casualties (at this time, the use of FBG is limited to preliminary studies); and
- the common use of FGB-based discrete sensors in laboratories to measure strain and characterize rock-mass properties (Gage et al., 2010, 2011, 2013).

Distributed Temperature-Sensing (DTS) System

Theory

The underlying principle of DTS for long-haul measurements is mostly based on Raman scattering (an inelastic scattering phenomenon) combined with optical time-domain reflectometry (OTDR). A short pulse is transmitted into the fibre and the forward-propagating light generates Raman backscattered light at two distinct wavelengths from all points along the fibre, due to the interaction between the light and molecular vibrations in the fibre. The wavelengths of the Raman backscattered light are different from that of the forward-propagating light and are referred to as 'Stokes' and 'anti-Stokes' wavelengths. The amplitude of the Stokes and anti-Stokes light is monitored and the spatial localization of the backscattered light can be determined as long as the propagation speed (velocity) inside the fibre and the time over which the motion occurred are known (Figure 2). The amplitude of the Stokes light is very weakly dependent on temperature, whereas the amplitude of the anti-Stokes light is strongly dependent on temperature. The temperature profile within the optical fibre is determined by calculating the ratio of the amplitudes of the Stokes and the anti-Stokes detected light.

Another type of scattering that is sensitive to changes in temperature and strain is Brillouin scattering. The interaction between the light and acoustic phonons moving through the fibre causes Brillouin scattering. Brillouin scattering is less commonly used as a DTS system in the industry since it is substantially the weakest of the scattering effects and requires more stacking to enhance the signal.

Applications

Distributed temperature sensing has proven to be a noticeably promising method for providing spatiotemporal temperature data in the geosciences. This approach has been widely employed in geothermal energy projects as a cost-effective and environmentally sustainable method to monitor real-time temperature variations over short and long periods. Monitoring fracture development during stimulation

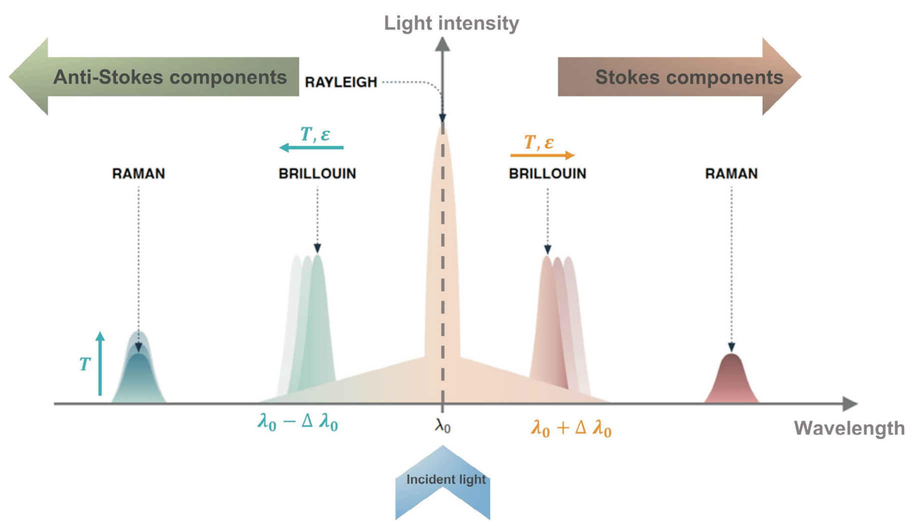

Figure 2. Spectra of scattered light in optical fibre. Rayleigh scattering occurs when the kinetic energy of the incident photons is conserved and, thus, the frequency of the scattered photons equals that of the incident light. Unlike Rayleigh scattering, in Raman and Brillouin scattering the incident-signal spectrum shifts relative to the initial signal, and backscatter spectra occur at both the higher (anti-Stokes) and lower (Stokes) frequency shifts. The intensity of the Raman upshifted-frequency component (anti-Stokes light) is strongly temperature dependent, whereas the intensity of the Raman downshifted-frequency component (Stokes light) is only slightly temperature dependent. Brillouin scattering occurs at a predictable amplitude but with variable frequency (modified from Pendão and Silva, 2022).

and fracturing, monitoring chemical injection during or after a fracturing job, providing permanent monitoring of injector and producer wells to allow identification of the precise zones and fractures that produce fluids as well as monitoring well integrity are just a few of the areas in which it has been applied (Sakaguchi and Matsushima, 2000; Coleman et al., 2015; Read et al., 2015; Sellwood et al., 2015; Freifeld et al., 2016; Patterson et al., 2017).

This technology has also shown success in a range of other applications, including as an early-warning system for coal-mine fire detection, as well as for petroleum pipeline-leak detection and concrete dam-crack monitoring. This system has also recently gained popularity for tasks such as monitoring reservoirs, earth dams, water channels, embankments, tunnels and levee seepage (Ravet et al., 2017, 2019; Nicholas and De Joode, 2022).

Furthermore, its applications extend beyond field measurements. The system outperforms conventional strain gauges in measuring axial and circumferential strains in rock samples. In addition to providing results tolerably consistent with those gathered by strain gauges, results obtained with DTS also indicate the exact location on a rock sample where a fracture first appeared. As a result, a single DTS-system measurement is comparable with that obtained from combined uniaxial and acoustic-emission tests (Xu et al., 2020).

Distributed Acoustic-Sensing System

Theory

In distributed acoustic sensing (DAS), the phase of the backscattered laser (recorded by the interrogator unit) is used to generate continuous seismic array-type recordings at aperture settings that vary from millimetres up to tens of kilometres. As this pulse of light travels down the optical path, interactions within the fibre, which result in light reflections known as 'Rayleigh backscatter', are determined by tiny strain events within the fibre, which in turn are caused by localized acoustic energy. The backscattered light is recombined with a reference phase split from the outgoing pulse to measure the change in phase relative to the previous pulse (Figure 2). This photonic technique is also referred to as 'phase-sensitive optical time-domain/frequency-domain reflectometry' (φ-OTDR/OFDR). The DAS system records the strain of ground motion at virtual locations based on the time of flight of laser pulses termed 'channel'. The strain recorded at a channel is the change in length over a reference length, referred to as the 'gauge length'. As a result, DAS recordings are inherently array measurements. The linear distance between any two virtual Rayleigh scattering points in the fibre core used to make one DAS measurement is in the order of 100 μm based on current telecommunication-grade optical fibre standards (Hartog, 2017).

Compared to Raman and Brillouin scattering, Rayleigh backscattering is considered a direct sensing mechanism and is used to measure environment-dependent propagating effects, due to being intrinsically independent of any external physical fields that may affect the surrounding environment.

Applications

The early 2010s saw the emergence of DAS applications in seismology and geophysics. The primary application of DAS in the energy industry has been to downhole vertical seismic profiling (VSP) and flow detection. It has now become a prominent substitute for VSP sensors (Daley et al., 2013; Li et al., 2015; Hartog, 2017; Martin et al., 2017). Performance of DAS sensors in VSP has been compared to that of conventional sensors through comprehensive investigations and DAS has demonstrated significant advantages over them (Mateeva et al., 2012; Daley et al., 2013; Correa et al., 2017; Lindsey et al., 2017; Wang and Gage, 2017; Jousset et al., 2018; Ajo-Franklin et al., 2019; Becker and Coleman, 2019; Lindsey et al., 2019). Table 2 provides a summary of this comparison.

Additionally, companies are showing increasing interest in the system for petroleum engineering projects such as microseismicity monitoring during hydraulic fracturing, fluid-flow monitoring through production and pipeline monitoring (Daley et al., 2013; Webster et al., 2013; Bakku, 2015; Karrenbach et al., 2017; Ni et al., 2018). Beyond

Table 2. Comparison between different types of geophysical sensors.

Geophysical sensors	Geophone	Hydrophone	Sonic tool	Distributed acoustic
Measurement type	Single point	Single point	Single point	Continuous
Measurement duration	Short-term	Short-term	Short-term	Short-/long-term
Surface measurements	No	No	No	Yes
Signal-to-noise ratio	Yes	Yes	Yes	Yes
Static loading	No	No	No	Yes
Dynamic loading	Yes	Yes	Yes	Yes
Cost	High	High	High	Low
Restrictions	Can't be used in harsh environments	Being a single-point measurement, has caused restrictions on the channel spacing	Only works in fluid-filled well	Being a single-point measurement, has caused restrictions on the channel spacing

these applications, DAS is also being relied upon for critical-infrastructure monitoring, border surveillance and transportation monitoring (Quinn, 2021; White et al., 2021).

Since 2015, academic and government researchers have shown increased interest in DAS to assess the feasibility of applying it to the study of earth systems. As a result, the number of publications on DAS has increased; however, in several areas, the research being conducted is restricted to the laboratory scale (Xue et al., 2014; Xu et al., 2015; Damiano et al., 2017; Lei and Hashimoto, 2019; Zhang et al., 2020). At present, DAS has not been employed in the mining industry, but DAS arrays could theoretically piggyback, with appropriate ground-motion coupling, on other fibre-optic monitoring systems to characterize rock-property variations or to detect and locate rock bursts induced by mining activity.

Summary

Discrete and distributed fibre-optic sensors have attracted remarkable attention in geoscience projects, due to their advantages over pre-existing measurement techniques and sensors. Their lower cost, immunity to electromagnetic interference and long-term stability compared to conventional sensors may enable the permanent installation of these types of sensors as part of a project to perform lifetime measurements in an early-warning system.

Not only could distributed fibre-optic sensors provide the profile of parameter variation over a greater distance than discrete fibre-optic sensors, but they also present the advantage of providing continuous measurements. In addition, distributed sensors are more cost-effective and have a higher spatial resolution. Because of these advantages, extensive research is ongoing as to how they might lend themselves to applications in several geoscience fields.

The use of fibre optics in geoscience projects in British Columbia and elsewhere will lead to significant improvements in measurements and cost savings and, most importantly, to a decrease in human casualties. In particular, deep-mining projects, which are extremely arduous to carry out because of their difficulty of access, may benefit greatly from further research into the use of fibre optics in geoscience projects. Lack of proper measurements in deep-depth projects results in less than optimal design performance and costly mistakes that, on some projects, result in lost value in the range of tens of millions of dollars.

Future Research Directions

The findings of this study will be used to demonstrate the potential applications of fibre optics in geoscience projects to develop novel methods of stress measurement. In addition, the study will be used as a guide for choosing a reliable sensing system for a deep-depth project, including block caving, designed to collect strain and stress measurements (S. Hendi, work in progress).

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