Chapter

Distributed Optical Fiber Sensing in Railway Engineering

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Abstract

There are many technologies associated with optical fiber sensing (OFS) and depending upon the type of application, a specific OFS technology plays a crucial role in the associated application as compared to the use of conventional sensing technologies with these applications. The same is true with the railway industry and the two most suitable OFS technologies in the railway sector are distributed acoustic sensing (DAS) and fiber Bragg grating (FBG). The two mentioned technologies in association with the railway industry are explained briefly in this chapter.

Keywords: distributed optical fiber sensing, distributed acoustic sensing, Brillouin optical-fiber time domain reflectometry, Brillouin optical-fiber time domain analysis, Raman-based distributed temperature sensing

1. Introduction

The services, such as cargo and mass traveling using the railway infrastructure, have undergone tremendous progress in recent years due to their reliability and safety in comparison to other modes of transportation. However, there is a possibility of degradation in both the railway vehicles (trains/trams) and infrastructure (track lines and the associated hardware) due to an increase in the speed limit, especially in the high-speed railway sector. This degradation normally leads to an increase in accidents. In under and non-developed countries, these accidents are inevitable due to the high cost of maintenance requirements for railway vehicles and infrastructure. Therefore, both the rolling stock and vehicles require reliability and low-cost operational monitoring.

In all of the mentioned metrics, infrastructure and vehicle are the two subjects, the attributes of which can be measured. The conventional operational monitoring systems for the mentioned subjects are usually cost-effective, but this cost-effectiveness is at the expense of unreliability if compared to the current optical fiber sensing (OFS) system. A dedicated monitoring (either operational or traffic management) technique can be used to measure one of the mentioned subjects which is more expensive than using a single method to measure both subjects with reliability. With these factors in mind, conventional sensing techniques in the railway sector can be regarded as expensive. Other than addressing a single metric and unreliability, there are many other aspects of the conventional techniques that make these methods expensive when compared to OFS. For example, a very high amount of electricity is consumed with the track circuits (TC) technique, or a very large number of sensors are normally installed to cover the operational monitoring of both the vehicles and infrastructure in the case of communication-based train control (CBTC).

A reliable sensing system refers to a number of factors, including the avoidance of dead sensing points, ease of installation, resistance of electromagnetic interference (EMI), and avoidance of safety hazards. Compared with the distributed optical fiber sensing (DOFS) technologies, the conventional railway-oriented sensing techniques are unreliable because there is no such method used by these techniques for measuring the distributed sensing, and hence there is a possibility of a large number of dead points leading to the provision of unreliable services. To avoid the possibility of dead points, there are chances of installing a myriad number of wireless sensors, but the energy requirements are challenging to meet the objectives. If wired sensors are installed instead, the number of power and communication lines will be very large, and the system installation may be impractical. Moreover, a long-term testing and assessment procedure of a fiber optic-based railway infrastructure is possible due to the possibility of high spatial resolution based on distributed and quasi-distributed nature of sensing. Such a distributed sensing system removes the necessity of power and data cables because it serves a dual purpose; sensing system with no active power requirement and as a communication system, thus reducing the cost tremendously for tens of kilometers distance span. Therefore, the difficulty of installing a myriad number of sensors in conventional sensing is less competitive than the OFS-based solution for both cost and reliability. EMI is another issue in electrical-based sensing systems, especially in very high voltage pantographs, which can be avoided with OFS as the light is the only signal passed through optical fibers. To avoid the difficulty of providing dedicated power and communication lines, TC provides a reasonable solution to cut off the additional power lines. However, this technique does not meet the standard safety requirements, which leads to an extreme sense of unreliability in case of avoidance of safety hazards.

Any railway system requires technology to help in the operational monitoring, train traffic management, and an additional amount of data for postaccident investigation. Operational monitoring is actually the structural health monitoring of a railway system, and it is based on the investigation of both the vehicle and its infrastructure. In the case of railway vehicle traffic management, any sensing solution may provide the instantaneous location, instantaneous speed detection, and live tracking of the vehicle, and these parameters are enough to control and manage the overall traffic. As the number of accidents is increasing in economically poor countries, the third benefit that any railway system can take from the technology is the acquisition of enough data, which can be beneficial in case of postaccident investigation, which is helpful to know the potential reason for the incident to avoid in the future. Other than manual inspection, several methods have been adopted so far to automate the operational monitoring of railway vehicles and infrastructure. These methods include CBTC, TC, wheel counters, track recording cars, and onboard operational monitoring.

The data, acquired in the case of conventional railway-based sensing systems, is discrete with a relatively large interval among spatial data samples if compared with any OFS-based technology. Any technology associated with DOFS sensing is normally distributed in nature, whereas there are also discrete sensing technologies in OFS such as fiber Bragg gratings (FBGs) and interferometry-based sensing solutions. However, there is a possibility of alleviating the distance between adjacent point sensors in the case of discrete or quasi-distributed OFS in a handful of ways if compared to the conventional sensing solution. Therefore, acquiring data with minimal distance among spatial locations is possible with OFS, and this large number of data has numerous other benefits.

A discrete sensing with a relatively large interval among sensing points may help in the case of operational monitoring but in the case of traffic management and postaccident analysis, this is surely a poor solution. The reason that continuous sensing or discrete sensing with relatively short intervals among sensing points well suits traffic management and postaccidental analysis is that data is critical at every possible point in these applications. For example, instantaneous speed and position determination are critical in the case of traffic management due to the high speed of railway vehicles. Missing data due to dead points may create severe problems, which may lead to a train-to-train collision. Moreover, postaccidental analysis requires data separated spatially in close vicinity in order to make the investigation possibly easy. Therefore, the sensing points, located spatially in close vicinity, can be used for any of the application that falls under any of the three groups of applications, as discussed. However, keeping the reliability factor in mind one may target only the applications that fall under the category of operational monitoring if the sensing points are not closed enough. This conclusion leads to the fact that the selected OFS technologies provide an edge due to their capability of spatially close sensing points or distributed sensing nature if compared with conventional sensing technologies.

Over the last two decades, the OFS-based smart railway infrastructure has made tremendous progress in view of research and development as optical fiber is always preferred due to its lightweight, reliability, and cost-effectiveness. The additional benefits of these systems include their lightweight nature and the possibility of distributed sensing solutions. In the case of train tracks, there is no possibility of data disruption while the vehicle passes within the tunnels as it normally occurs in case of the navigation systems such as the Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS), etc. Unlike the conventional sensing technologies in the railway sector, which measure only the frequency spectrum, the technologies associated with OFS not only measure the frequency spectrum but also the true phase of the time-based signals. Therefore, to prevent catastrophic failures and early failure detection, the real-time sensing nature of OFS-based systems is a better option if compared with the conventional sensing system. In short, OFS can be regarded as the only reliable and cost-effective solution for smart railways. Other than management system, operational inspection, and providing ease of postaccidental investigation, some technologies in OFS can also provide intrusion detection and trespassing monitoring.

In summary, OFS-based sensing systems are not only capable of targeting both the subjects (railway infrastructure and vehicles) with a single sensing system but also provide cost-effectiveness and reliability in addition to other benefits. Therefore, in comparison to the conventional operational monitoring techniques, OFS-based systems can be considered to be more suitable with the provision of long-term solutions for several types of maintenance and other miscellaneous monitoring for both the vehicle and infrastructure.

2. Optical fiber sensing

Light travels within the optical fiber and constrains itself in the medium due to the total internal reflection mechanism of light signals. This total internal reflection is possible if the light tries to pass from the highly dense medium to a lower one and the concept of this principle is depicted in **Figure 1**. **Figure 1** shows that a deflection away from the reference occurs if the light signal passes from a highly dense medium to a low dense medium. If the incident signal surpasses the critical angle (θ_3 in our case), the total internal reflection occurs. The same figure shows the total internal reflection occurs at the incident angle θ_5. Within an optical fiber, the light traveling follows the principle of total internal reflection. The two main components of an optical fiber are a core and a cladding, as depicted in **Figure 2**. The core is the highly dense medium, whereas the cladding is a low dense medium. Light is injected from one end of the optical fiber and due to total internal reflection, the light retains within the core until it reaches the end of the optical fiber.

The conventional vehicle and track monitoring systems are mostly based on electrical principles. The main use of optical fibers is in the telecommunication industry. However, the idea of OFS in railway systems was engendered to avoid EMI, which is considered to be a more challenging impairment than any other drawback of electrical-based systems. Later on, many other OFS-based solutions were used in comparison to the conventional sensing techniques in the railway industry. By that time, the OFS solution got popular, and many challenging issues of the railway infrastructure were resolved with the OFS solutions, especially in the last two decades.

DOFS is a specialized group of technologies under OFS, that provide sensing at any location of the fiber, where needed and the sensing can be done simultaneously at

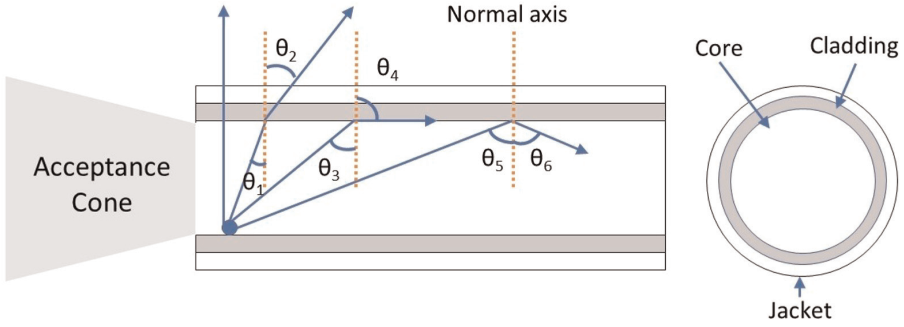

Figure 1.
A demonstration of total internal reflection.

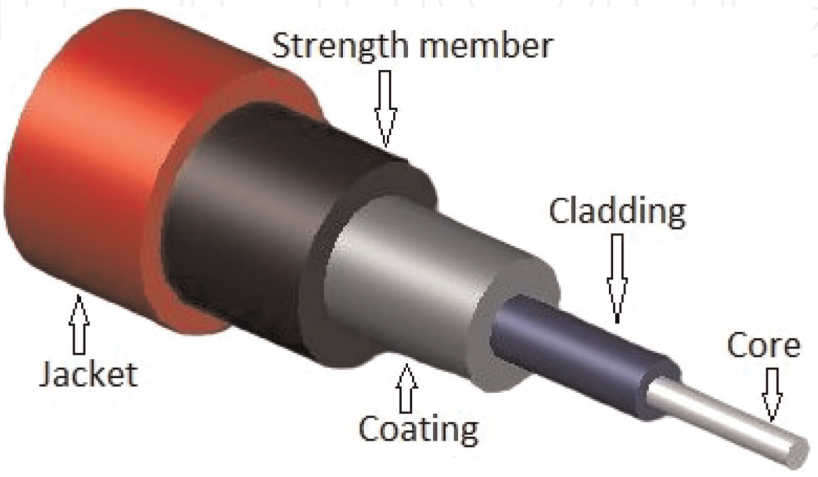

Figure 2.
Cross-section of an optical fiber cable.

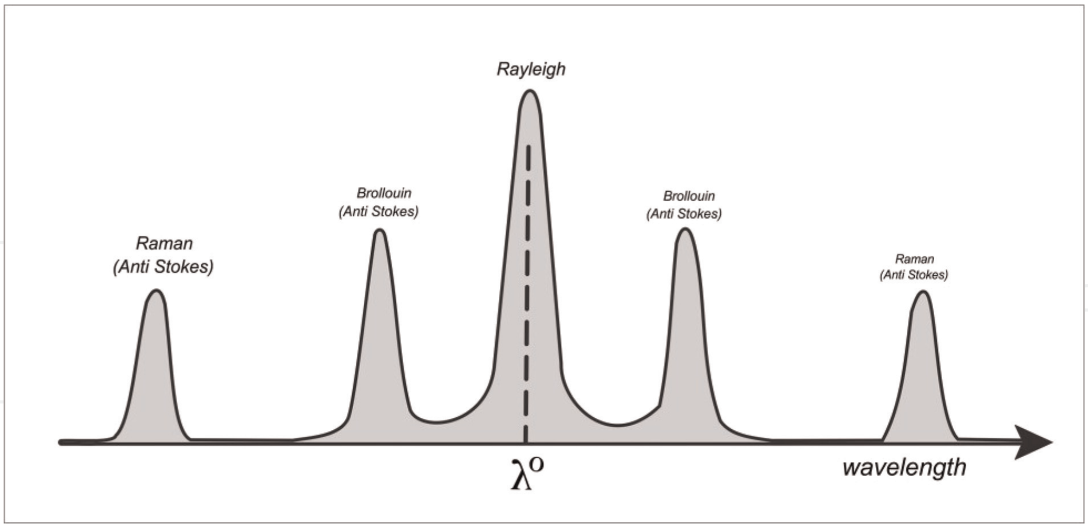

Figure 3.
Typical operating spectrum of different distributed optical fiber sensing technologies.

multiple locations. The DOFS-based technologies are grouped based on three types of light wave scattering. These are Rayleigh scattering, Brillouin scattering, and Raman scattering [1]. The frequency band of each of these scattering types is different, and an overview of these bands is depicted in **Figure 3**.

All of these scattering types are comprised of many other sensing technologies. For example, the technologies associated with the Rayleigh scattering include distributed acoustic sensing (DAS) or phase optical time-domain reflectometry (ϕ-OTDR), and polarization-OTDR. In regard to the railway industry in the last decade, the focus in the railway sector is mainly on DAS as compared to other Rayleigh-based scattering technologies.

DAS can be used in distributed and quasi-distributed nature sensing, and there is a possibility of dynamic stress sensing for both the railway vehicles and the infrastructure. Moreover, due to the possibility of supporting a very long range, train tracking, and operational monitoring have achieved a high level of maturity in the research field associated with DAS technology for its use within the railway sector. On the other hand, Brillouin scattering-based DOFS technologies include Brillouin optical time domain reflectometry (BOTDR), Brillouin optical time domain analysis (BOTDA), and Brillouin optical frequency domain analysis (BOFDA). However, due to the hybrid sensing capability of Brillouin scattering-based technologies can be rarely used in railway infrastructure monitoring as the high temperature of the railway tracks may affect the measured stresses. Beside, Raman scattering-based sensing technologies are not very popular in the railway industry due to their only sensing capability for temperature and relatively less response to a rapid change in a measured quantity. Moreover, Raman scattering-based sensing technologies only measure the temperature in a distributed manner, but this technology can be expensive for use in the railway sector. Many other OFS-based technologies, such as interferometry-based sensing techniques, can be regarded as unreliable in the railway industry due to their nonlinear nature, and hence cannot be used to meet the required objectives. One of the advanced interferometry-based sensing technologies is the optical frequency domain reflectometer (OFDR), which is not popular in the railway sector due to its short-distance applications. It is due to these reasons that the use of FBGs and DAS technologies is dominant in the railway sector, and more. than 95% of the OFS-based research articles are based on these two technologies. Therefore, this chapter provides insight into both the FBGs and DAS technologies for their extensive use within the railway industry.

2.1 Fiber Bragg gratings in railways

FBGs are the best quasi-distributed alternative in the OFS field, and their use has become quite popular within the railway industry in the last two decades. As the FBGs can support a very long range of distances, and hence this technology has attracted the researchers' attention in the railway industry. Moreover, the use of any FBG type can provide the dynamic sensing capability, which has attracted its interest in the railway industry.

With distributed sensing, the whole optical fiber can act like an array of continuous sensors at virtually no gap among the sensing points. Moreover, the same fiber can be used as a communication medium, and hence the ease of installation make these sensors a favorite choice. On the other hand, the quasi-distributed sensing points at a relatively low gap among the sensing points can be achieved with ease of installation with the help of FBG. These sensors are normally the best alternative to the conventional sensing used within the railway sector. FBGs are formed with the help of an intense optical interference pattern within a fiber core. These patterns are formed such that the grating acts like a periodic perturbation of the refractive index. The gratings can perform many functions such as filtering, diffraction, and reflection. However, the most important property of these sensors is the reflection of incident light waves according to a predefined wavelength. The FBGs can be embedded within the optical fiber at discrete positions, as shown in **Figure 4**. These sensing points are generally comprised of a periodic modulation of the refractive index, which is normally embedded in the core of a single-mode optical fiber. There are two types of these gratings, uniform and nonuniform grating. The phase fronts of the uniform grating are usually vertical to the longitudinal axis of the fiber. After the light strikes along the grating plane, it gets scattered along the core part of the fiber, as shown in **Figure 4**. The period of modulation index plays a very important role in controlling

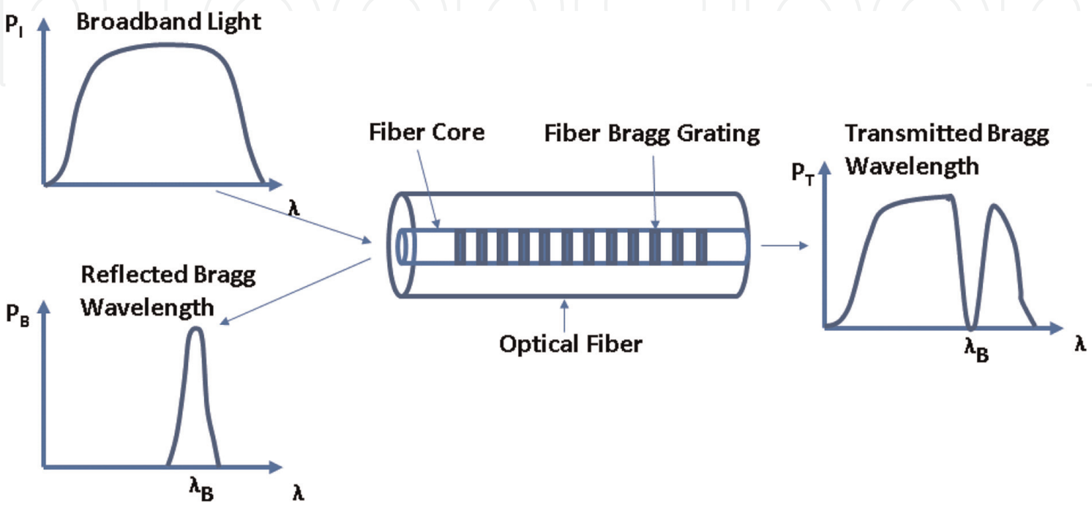

Figure 4.
A demonstration of FBG, passing and reflecting the selective frequency components.

the width of the frequencies scattered by the grating, and this index is represented by Λ, which can be defined as

$$\Lambda = \frac{\lambda_B}{2n_{eff}} \tag{1}$$

Where λ_B is the Bragg wavelength of the input light, which is back-reflected from the grating plane, and n_{eff} is the effective index of the optical fiber.

The important aspect of the grating period is that the wavelength of the reflected light is modified in accordance with the grating period due to a change in external environmental effects such as temperature or applied stress. It is due to this reason that a change in the external environmental conditions is proportional to a change in the refractive index of the core and the modulation index Λ, and this, in turn, provides a proportional change in temperature and applied stress. In other words, a change in both the external variables (stress and temperature) brings an offset to the Bragg wavelength λ_B, and the whole process is demonstrated in **Figure 4**. This figure depicts that the light waves are reflected according to the predefined wavelength gratings, and hence pass the remaining wavelengths of light. The reflected wavelength is processed such that the environmental effects such as strain or temperature are numerically acquired, and hence detection of a change in wavelength provides useful information about the measured variable.

The use of FBGs is becoming quite popular in the railway industry in regard to the monitoring and inspection of both the vehicle and track and the previous research shows a great deal of work in this area than DOFS as far as the railway sector is concerned. FBGs are popular in railway operational monitoring due to their small weight and volume, ease of handling, high spatial resolution, high precision and accuracy in the numerical results, and the capability to multiplex multiple signals simultaneously due to the wave division multiplexing capability of the fiber optics. By using a spacing between each FBG sensing point of less than 1 km, it is possible to extend the measurement range up to 100 km.

Literature reveals that FBGs in the railway sector have been used for the first time in the year 2004 for derailment detection [2] and axle counting [3]. Since then, these sensors have been used in a myriad of different applications in the railway infrastructure and the associated vehicles. The derailment detection was used as a metric for identifying different train types, whereas axle counting was used as a metric to detect the vehicle speed. After the initial steps were taken, the railway sector used FBGs in a number of applications such as the detection of defective wheels [4, 5]. These sensors were installed in the vicinity of the sleepers for health monitoring of both the rails and the vehicle's wheels status and proved the metrics such as "infrastructure measuring infrastructure metric" and "infrastructure measuring vehicle metric." The two metrics measurements were possible with the help of elegant signal processing techniques, which was otherwise impossible without the use of FBGs. Moreover, the train moving direction and axle load were measured along with many other important parameters in [6]. Beside the rail and infrastructure monitoring, the FBGs were utilized by bonding them to the railway tracks in order to measure speed and track the moving vehicles along the whole distance [6–8]. Beside, the innovative FBG interrogator has been designed to measure the train speed and axle load with a minimum possible number of FBG sensors [6]. Due to the ease of installation of FBG sensors and systems, the applications of these sensors in the railway sector did not end till the stage of limited monitoring as we can see in the case of conventional sensing systems.

These sensors can be installed in brack blocks, wheels, axles, and bogies in order to complete a composite sensing system, as installed by Mi in [9]. Such a composite sensing system can provide a complete monitoring system, which was otherwise impossible without the use of FBGs. Aside from these, different force types such as longitudinal and vertical forces on the railway tracks are possible with FBG [10, 11]. To filter out the impact of temperature from the strain measurements, efforts were made in [12], and hence there is a possibility of a provision of pure strain measurements even in the harsh environment where a large variation in temperature is possible. The benefits of FBGs in the railway industry are not limited to the mentioned applications. Vibration measurement in geogrid-reinforced ballast and unreinforced ballast along with the lateral displacement were made [13]. Moreover, FBGs can be utilized for the differential settlement of railway tracks [14]. Additionally, the operation monitoring/inspection of switchblades, fishplates, and stretcher bars is possible with the help of FBGs [15]. An important part of the railway infrastructure is the railway bridges. The effects of transverse vibration, dynamic load bending, and vertical deflection of the railway bridges were inspected in [16]. FBGs were proven to replace the electrical based sensing systems such as strain gauges, and this was verified by inspecting the vertical acceleration and contact force in pantograph catenary [17]. **Table 1** refers to different railway-specific applications associated with the use of FBGs.

S. no	References	Year	Work purpose
1	[18]	2018	Fiber-optic Bragg sensors for the rail applica-tions
2	[19]	2022	Smart railway traffic monitoring using fiberBragg grating strain gauges
3	[10]	2015	Longitudinal force measurement in continuouswelded rail with bidirectional FBG strain sensors
4	[20]	2016	The longitudinal force measurement of CWRtracks
5	[21]	2011	Strain measurements and axle counting inhigh-speed railway applications
6	[22]	2022	Discriminative monitoring of seamless railforce
7	[2]	2004	Derailment detector
8	[3]	2004	Axle counting
9	[8]	2016	Railway track operational monitoring
10	[11]	2012	Structural health monitoring of railway tracks
11	[12]	2017	Monitoring and early warning system of high-speed railway track operational monitoring
12	[6]	2016	Railway infrastructure operational monitoring
13	1	2016	High-speed railway operational monitoring
14	[23]	2016	High-speed railway operational monitoring
15	[24]	2012	Real-time railway traffic monitoring
16	[4]	2013	Wheel flat detection in high-speed railwaysystems
17	[7]	2007	Railway infrastructure operational monitoringand train tracking
18	[25]	2018	Railway operational monitoring system
19	[26]	2005	Bridge load measurement under the movingtrain load
20	[27]	2007	Railway track operational monitoring

S. no	References	Year	Work purpose
21	[28]	2012	Performance analysis of peak tracking tech-niques
22	[9]	2014	Composite railway health monitoring system
23	[13]	2015	Rail track deformations monitoring
24	[14]	2016	Railway track differential settlement monitor-ing
25	[15]	2016	Novel liquid-based FBG design for sensitivityand temperature range enhancement
26	[29]	2012	Design of a novel FBG-based sensing systemfor train vibration and weight measurements
27	[30]	2014	First work to conduct continuous structuralhealth monitoring systems on railway pantographs
28	[5]	2015	Rail and wheel wear monitoring by acquiringthe data for a very long time (6 months)
29	[17]	2013	FBG-based sensing system was proved tooutperform in comparison with conventional sensing systems in high voltage pantograph-catenary monitoring systems.

Table 1.
Applications of FBGs in references to previous work.

2.2 Distributed acoustic sensing in railways

DAS works under the principle of ϕ-OTDR, and it is a Rayleigh scattering-based DOFS technology used to sense the vibrations and perturbations at a regular or selected spatial point along the entire length of the optical fiber. Each sensing point is analogous to thousands of hydrophones connected in series. According to the working principle of DAS, the light signals from a laser source (around 1500 nm wavelength) are modulated with rectangular pulses, and these pulses are sent to the fiber under test (FUT). Each segment of the FUT reflects the Rayleigh backscattered signals, and a circulator is used to divert these back-reflected signals to the direction other than the one from which these pulses originate. At the intended port of the circulator, the photodetector is installed, which converts the modulated pulses into electrical signals. A positive aspect of the DAS system is that the simultaneous perturbed signals can be retrieved without any specialized signal processing system. The two most commonly used configurations of a DAS system are directed detected and coherent detected systems, as shown in **Figures 5** and **6** respectively. The configuration in **Figure 5** is the direct detected system that implies there is no reference light source at the photodetection stage. A coherent detected ϕ-OTDR system is one in which the laser source acts as the reference signal to provide additional phase information at the photodetection stage. Converting the direct detected system to a coherent detected system requires a modification such that the laser source is divided into two parts with the help of a coupler. One of the branches of this signal is injected into the optical modulator, whereas another part of the same signal leads to the balanced photodetector, as depicted in **Figure 6**.

In both the direct and coherent detected systems, the optical modulator is considered to be any type of acousto-optic modulator (AOM) or electro-optic modulator (EOM) with a high extinction ratio (a ratio between transmitted one and transmitted zero). The modulation drops the signal strength many folds, and therefore an Erbium-

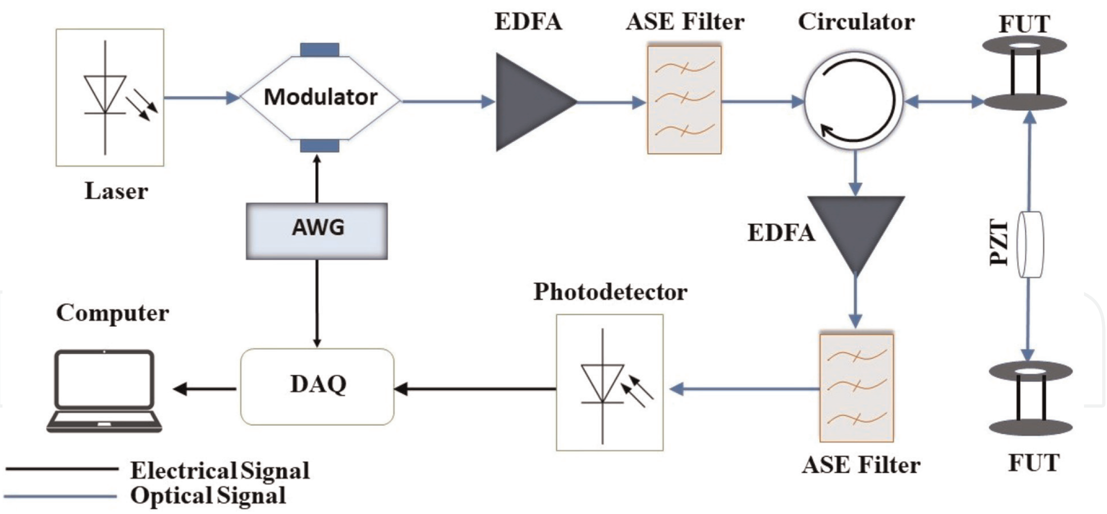

Figure 5.
A direct detected ϕ-OTDR system.

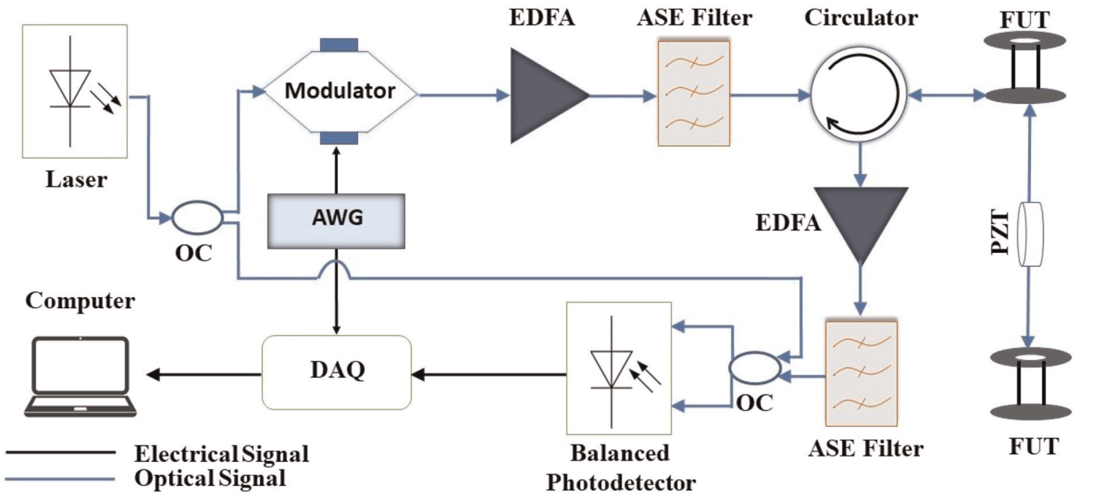

Figure 6.
A coherent detected ϕ-OTDR system.

doped fiber amplifier (EDFA) is used to amplify these signals. The EDFA and filters are optional and these devices are installed if needed in the very large L_{FUT} (length of FUT) applications. Each injected pulse with a predefined pulse width (PW) within the fiber defines the spatial resolution (SR) of the measured distance within which the perturbation is felt. These pulses are injected within the fiber with a specific pulse repetition rate (f_{PRR}), and the backscattered signals are acquired with the sampling frequency of f_{DAQ}. The maximum frequency (f_{PER}) from the frequency components generated due to applied perturbation is another factor, that is. restricted due to the associated parameters. Here is a list of compromised parameters that depend on another parameter and are mentioned below with examples (**Table 2**).

Two types of sampling rates are defined in the abovementioned discussion. One of these types relates to the spatial sampling rate, and its speed depends on the sampling frequency of the data acquisition (DAQ) card, termed f_{DAQ}. The second type relates to the temporal sampling rate, and its speed depends on PRR. From the length of a fiber, one can decide the maximum allowable frequency of the perturbation. The smaller the length of the fiber, the higher will be the frequency at which the perturbation can be

Compromise between L_{FUT} and f_{PRR} A typical length of the FUT restricts the maximum f_{PRR} at which the pulses are injected. Formula: $f_{PRR} = c/(2 \times n_{eff} \times L_{FUT})$, where c = velocity of light.	
Example-1	L_{FUT} of 1 km fiber can allow a maximum of f_{PRR} = 100 kHz against each sensing points.
Example-2	L_{FUT} of 500 m fiber can allow a maximum of f_{PRR} = 200 kHz against each sensing point.
Compromise between f_{PRR} and f_{PER} PRR restricts the maximum frequency of the applied perturbation. $f_{PER} < f_{PRR}/2$	
Example-1	f_{PRR} of 10 kHz can permit all frequencies under f_{PRR} = 5 kHz of the applied perturbation
Example-2	f_{PRR} of 5 kHz can permit all frequencies under f_{PER} = 2.5 kHz of the applied perturbation
Compromise between SR and f_{DAQ} **Spatial resolution (SR) restricts the sampling rate of a DAQ card (f_{DAQ})** **$SR = c/(3 \times f_{DAQ})$, where c = velocity of light and the unit for SR is in meters.**	
Example-1	SR of 1 m (10 ns pulse width of pulse) requires the DAQ card with a minimum sampling rate of f_{DAQ} = 100 MHz.
Example-2	SR of 0.1 m (1 ns pulse width of pulse) requires the DAQ card with a minimum sampling rate of f_{DAQ} = 1 GHz.
Compromise between PW and SR PW controls the SR. $SR = c \times PW/(2 \times n_{eff})$, where c = velocity of light (m/sec), n_{eff} is the effective refractive index, and PW is the pulse width (in seconds).	
Example-1	A PW of 2 ns (Function generator frequency of 500 MHz) can provide a minimum of SR = 20 cm spacing between two sensing points.
Example-2	A PW of 1 ns (Function generator frequency of 1 GHz) can provide a minimum of SR = 10 cm spacing between two sensing points.

Table 2.
Threshold of the limiting parameters.

detected. Both the SR and the DAQ sampling rates are required to define the minimum spacing between two sensing points. The lower the SR and DAQ sampling rate, the smaller the spacing between two sensing points. Moreover, the lower the SR and DAQ speed, the smaller the spacing between two sensing points. After sending a single pulse, the fiber provides a response signal and each of these samples correspond to a distance 1/PRR in the time domain, where the mentioned response signal is the result of Rayleigh backscattered signals along the whole FUT. The correspondence distance of this response in meters can be obtained using the formula: $L_{FUT} = c\ 2\ n_{eff}\ f_{PRR}$. The response against the whole FUT is called a single trace, which is a stationary random process, and this fact can be observed with the help of observing each received trace provided that the fiber is not disturbed with the assumption of the very long linewidth of the laser source. Differentiating one received from its previous counterpart is termed the differential data-trace. One can easily observe the phase change due to the applied perturbation with the help of a differential data-trace. In case of any perturbation, multiple traces are normally acquired, and the difference of each subsequent trace is taken in order to determine the point of perturbation.

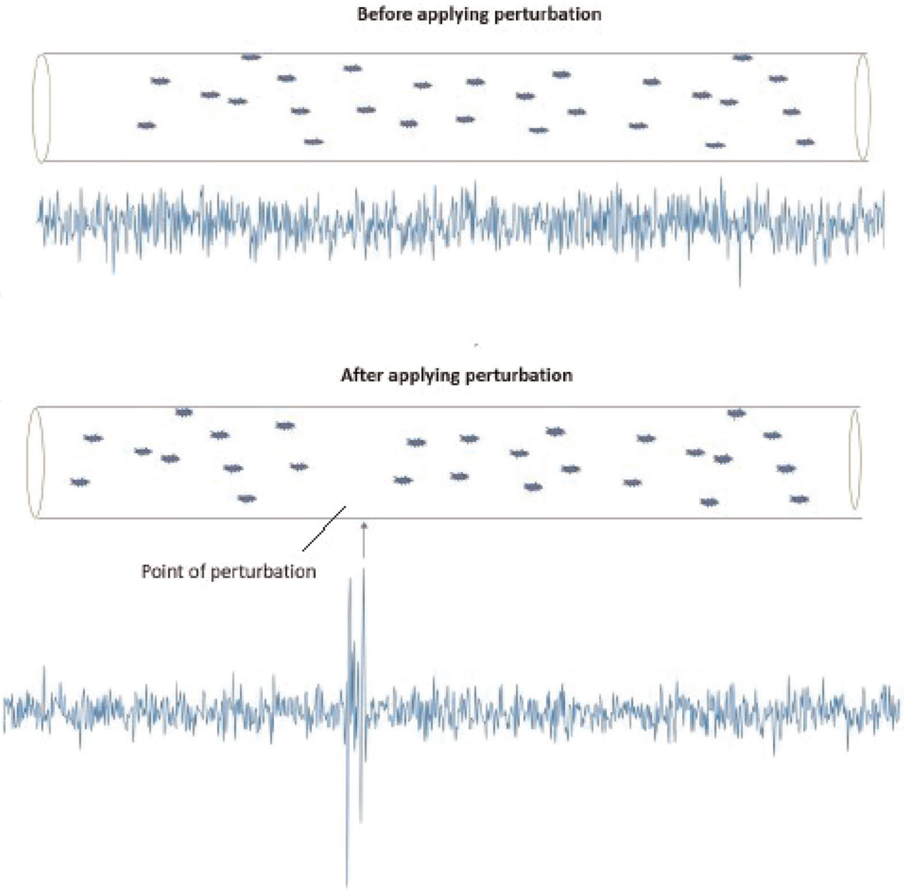

Figure 7.
Perturbation demonstration using differential signals of ϕ-OTDR system.

A schematic diagram showing the behavior of differential signals due to a stretch of the fiber by an applied perturbation is shown in **Figure 7**.

DAS is a revolutionary photonic sensing technology that exploits the use of a standard communications fiber into a linear array of discrete vibration sensors. Activities such as people walking/running, hot-tapping pipelines, pipeline leakage detection, perimeter intrusions, moving vehicles, industrial operations, failing mechanical components, firing direction detection, and many applications are responsible for generating vibrations with distinct acoustic characteristics. DAS technology monitors these vibrations and accurately detects, classifies, and reports on the vibration events. With DAS, there is no need to install the conventional sensors, and a simple G.652 type single-core fiber optic cable is enough to sense the whole distance in a distributed fashion, and hence it saves a huge amount of cost among hundreds of kilometer distance spans. The efficient algorithms requiring very few data traces [31–33] can help to calculate the instantaneous speed of the trains. As we know, terrorist acts along railway tracks, derailments, and train collision accidents were quite common in the history of railway-based accidents; therefore, DAS can play a very important role to avoid these accidents in the future. The use of DAS technology in the railway sector is not only a cost-effective solution but due to the provision of enormous data at each spatial location also there is a possibility of involving artificial intelligence to automate both the security and train tracing along the whole railway track, which is normally in hundreds of kilometers range. Fiber response or traces received against a few injected pulses are mostly insufficient to detect a certain perturbation as most differential data traces do not describe the effect of external perturbations. Most often, the machine learning algorithms applied to these differential data traces do not provide essential information for classifying different types of intrusions unless a myriad number of data traces are acquired. Normally, a single data trace is received with a certain delay after the injection of a single pulse within an optical fiber. A large percentage of the received data traces are irrelevant, and these irrelevant data traces are also received with the same delay. Hence, DAS can be successful in many applications for which the delay is not important. However, in the case of high-speed moving trains, where instantaneous intrusion detection, instantaneous speed determination of the trains, and the instantaneous location of each wheel of the respective bogies of the whole train are solicited, the lag in the DAS system is unacceptable. There are many applications of the DAS system, including fence, border, and pipeline security systems. Several signal processing methods applied directly on differential data traces include time-series-based algorithms [34–38], and frequency-based algorithms [39–41] approaches were suggested to provide a better probability of detection and classification accuracy in perturbation detection and event recognition applications respectively without imparting emphasize on utilizing a smaller number of data-traces efficiently. The time-frequency-based approaches such as discrete wavelet transform [42–44], Hilbert-Huan transforms [45], or similar algorithms [46–48] are best suited for trace-to-trace fluctuation-based noise alleviation [49, 50] than the frequency-based or time-series-based approaches. A drawback of the time-frequency-based approach is that these techniques are intensively parameter-dependent. For example, choosing a very selective mother wavelet and a vanishing moment in DWT-based algorithms for each specific event in a perturbation recognition application may not be possible, although, these algorithms can be suitable for the applications such as perturbation detection. The issues relevant to sampling data relevant to high-speed vehicles were suggested for the first time in [31–33], and hence now it is possible to consider DAS for very high-speed vehicles.

A detailed insight into DAS technology with respect to the railway infrastructure and the associated railway-based vehicles, whether trains or trams, is discussed here. DAS was first introduced by Juarez in the year 2005 while demonstrating the concept of intrusion detection, and this class of distributed sensing became popular afterward. Initial work was carried out on the ballastless track structure in the year 2013 [51] followed by speed and position detection in the year 2014 [36]. As mentioned before, the two main applications of any railway system are train traffic management and operational monitoring. The research work in the case of train traffic management includes speed and position precision improvement along with external applications such as security and other activity monitoring alongside railway tracks, whereas the operational monitoring applications involve continuous monitoring of both the train and tracks for their faults. **Table 3** includes the research work by exploiting DAS and ϕ-OTDR in traffic management of the railway system. Another important set of railway applications involves the operational monitoring of both the trains and tracks. **Table 4** shows the literature work regarding the use of the DAS system for operation monitoring of the railway system.

2.3 Other OFS technologies

The probable future technologies in the railway sector related to OFS are FBGs and DAS, as discussed. Other technologies linked with Brillouin scattering and Raman scattering have been investigated quite often in the railway sector. The reason is that

S. no	References	Year	Work purpose
1	[36]	2014	Traffic management along with the safety monitoring of the trains in the case of two parallel railway tracks.
2	[52]	2014	Traffic management along with the safety monitoring of the trains in the case of two parallel railway tracks.
3	[53]	2020	Speed precision improvement for a speed of up to 160 km/hr. train.
4	[54]	2015	Location, mass, and speed precision improvement
5	[55]	2015	Location precision monitoring
6	[56]	2016	Machine learning methods for alleviating false Alarms in train detection system using long-time recording.
7	[57]	2017	Intrusion detection system implementation for train and track security
8	[58]	2017	Construction monitoring alongside the railway infrastructure
9	[59]	2018	Segregating trains with the help of signatures
10	[60]	2019	Noise removal for increasing processing time for real-time train traffic management applications

Table 3.
Train traffic management applications of DAS in refs to literature.

S. no	References	Year	Work purpose
1	[51]	2013	Study of ballastless track structure monitoring by distributed optical fiber sensors on a real-scale mockup in a laboratory.
2	[61]	2016	Distributed acoustic monitoring to secure transport infrastructure against natural hazards—Requirements and new developments.
3	[62]	2018	Measurement of distributed dynamic rail strains using a Rayleigh backscattered based fiber optic sensor: Lab and field evaluation.
4	[63]	2020	Operational Monitoring of Railway Infrastructure

Table 4.
Train traffic management applications of DAS in references to previous work.

the technologies related to Brillouin-based scattering cannot differentiate between static sensings such as stress and temperature. An abrupt change in the temperature occurs after the train traverses the railway track, which provides confusion between the real measured variable (stress) and temperature. Though some efforts are made in this regard to adopt the Brillouin-based sensing technologies in railways such as traffic monitoring [64], railway infrastructure [65], track deformations monitoring [66], and operation monitoring of the railway infrastructure [67]. However, the mentioned research work is insufficient for these technologies to be adopted in the railway sector anytime soon. The reason the OFS technologies related to Raman scattering are not used in the railway sector is because of their use in temperature sensing only. A long-distance infrastructure monitoring with a temperature sensing-only application is not the cost-effective solution, and hence this sensing technology has not been investigated so far in this sector. Beside, the interferometric-based OFS cannot be used in the railway sector due to the nonlinear nature of this sensing, as well as the non-distributed nature. Though, [68, 69] have presented their work in interferometric-based sensing, but these techniques were not verified with a distributed or quasi-distributed sensing techniques over a very long range of railway track or vehicle. OFDR is another type of interferometric-based sensing technology with distributed nature of its sensing. However, due to its short-range applications, this type of interferometric-based sensing cannot be used in railway applications.

3. Summary

This chapter has presented a detailed description of the use of the OFS systems and their advantages as compared to the conventional sensing system for use in the railway sector. In a broad sense, the two categories of applications in any railway sensing system are comprised of operational monitoring and traffic management. Normally, dedicated sensing systems are utilized to implement these two types of applications using conventional methods. Postaccidental investigation can be termed as a third category of applications that is related to acquiring data from spatial locations with a minute gap among these locations, which was otherwise impossible in the case of a conventional sensing system. With OFS all three categories of applications are possible with a single sensing system due to its features such as the best reliability and cost-effectiveness to employ all these solutions in a long-range railway system. Moreover, there are additional benefits of OFS in the railway sector, that outweigh this sensing system as compared to conventional sensing systems. There are many sensing systems in OFS; however, in the railway industry, the popular quasi-distributed sensing system is FBG and one of the popular distributed sensing systems is DAS. The two sensing systems have been explained.

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