FIBER-OPTIC SMART STRUCTURES FOR MONITORING AND MANAGING THE HEALTH OF TRANSPORTATION INFRASTRUCTURES

Final Report

METRANS Project 09-13

April 2010

Principal Investigator: Chin Chang

College of Engineering/Department of Electrical Engineering

California State University

Long Beach, CA 90840

DISCLAIMER

The contents of this report reflect the view of the author, who is responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program, and California Department of Transportation in the interest of information exchange. The U.S. Government and California Department of Transportation assume no liability for the contents or use thereof. The contents do not necessarily reflect the official views or policies of the State of California or the Department of Transportation. This report does not constitute a standard, specification, or regulation.

ABSTRACT

The monitoring of transportation infrastructure health is currently reliant on transportation maintenance teams. Scheduled and periodic inspections of most infrastructures are performed by manual and visual operations, which are generally time consuming and costly procedures. The use of fiber-optic sensor technology makes it possible to realize continuous, real-time and automatic health monitoring for transportation infrastructures. In this report, we present the research results of the feasibility study on using fiber-optic sensors for transportation infrastructural health monitoring. Since the topic spans many disciplines, our goal is limited to providing a basic conceptual framework. We begin by reviewing the prerequisite topics of structural health monitoring and fiber-optic sensors, including a brief review of point and distributed fiber-optic sensor technologies. We then provide a comprehensive review of key fiber-optic sensors which may be used in transportation infrastructure monitoring. We discuss point fiber-optic sensors first, and then distributed fiber optic sensors. Performances of each sensor are discussed in the context of transportation infrastructure monitoring applications. We conclude the report with observations on the current directions of research in the field of fiber-optic sensors for transportation infrastructure health monitoring and we propose future research plans for the implementation of fiber-optic sensor technology.

Contents

LIST OF FIGURES

LIST OF TABLES

DISCLOSURE

Project was funded in its entirety under this contract with California Department of Transportation.

ACKNOWLEDGMENTS

The research team and especially Chin Chang are very grateful for the support of the METRANS Transportation Center. In addition, I would like to thank Mr. Etienne Constable of Roctest, Inc., for his valuable product information on fiber-optic sensors used for structural health monitoring applications. I would also like to thank Mr. Rahul Mehta, a graduate student of the Electrical Engineering Department, California State University, for his outstanding work in the fiber-optic Bragg grating sensors.

1. INTRODUCTION

The collapse of the Minneapolis Bridge has raised a public safety issue concerning the nation's 73,784 bridges that are rated "structurally deficient" by the Department of Transportation [1]. The improvement of bridge and overpass safety has since become a priority, in particular, after the accidental collapse of the Minneapolis Bridge. Knowing the integrity of in-service transportation infrastructures on a continuous, real-time basis is a very important objective for transportation maintenance teams. Economic factors are of course also central to the viable adaptation of a technology to the needs of public safety. A cost-effective and innovative technology is imperative for effectively monitoring and managing the health of bridges and overpasses without creating a substantial tax burden for all tax payers.

The monitoring of transportation infrastructures is currently reliant on transportation maintenance teams. Scheduled and periodic inspections of most infrastructures are performed by manual and visual operations, which are generally time consuming and costly procedures. Recently, Erik A. Johnson of the University of Southern California proposed an approach for bridge structural health monitoring based on variable stiffness and damping devices [2]. This approach offers the potential to provide more accurate parametric changes required for bridge health monitoring.

The use of fiber-optic sensor technology makes it possible to realize continuous, real-time and automatic health monitoring for the transportation infrastructure. This technology offers several advantages, such as minimized downtime, avoidance of catastrophic failure, and reduction in maintenance labor. In addition, any new design of the infrastructure may include fiber-optic sensors to make smart structures. With well-developed fiber-optic networking technology, a remote laser source may be used as a signal source to efficiently and accurately detect parametric changes at different locations in the structure. The detected information may be recorded and analyzed in order to obtain precise structural information on the infrastructure. In summary, the realization of a fiber-optic sensor monitoring system for the transportation infrastructure may greatly improve public safety with low operation costs.

The objective of the research project focuses on using fiber-optic sensor technology for monitoring the structural health and integrity of transportation infrastructures. Real-time, computer automated monitoring of the health of bridges and overpasses is essential to the safety of the general public living in major metropolitan areas. The proposed research project will investigate the feasibility and economics of the fiber-optic sensor for Transportation Infrastructural Health Monitoring (TIHM). There are many potential advantages to using the fiber-optic sensor for the TIHM application. In addition to its function as a nondestructive evaluator, it offers the ability to reconsider the enhanced design and full safety management of the structure. Moreover, a central monitoring and evaluation system may be implemented utilizing the existing wide area network. Thus, the long-term, in-service aging of the structure can be effectively monitored and evaluated. Finally, any acute damage from earthquakes, natural disasters, and terrorist attacks may be observed and assessed immediately for necessary post-disaster actions.

2. PROBLEM DEFINITION

A majority of the structural monitoring sensors used in long-span transportation infrastructure health monitoring systems is still based on conventional electric transducers. The Akashi Kaikyo Bridge in Japan, which is the world's longest suspension bridge, uses a seismometer, anemometer, accelerometer, velocity gauge, Global Positioning System (GPS), girder edge displacement gauge, tuned mass damper (TMD) displacement gauge, and thermometer for dynamic monitoring [21]. Some conventional sensors currently used in this long-span bridge health monitoring are deficient in providing adequate accuracy and long-term stability. For example, a GPS used in the Akashi Kaikyo Bridge for absolute displacement or deflection monitoring has three limitations: 1) the measurement accuracy of a GPS is not sufficient for bridge health monitoring requirements; 2) a GPS does not work well for monitoring the displacement of piers beneath the bridge deck (caused by ships colliding, settlement, etc.), and 3) a GPS is not capable of accurately measuring deflection in a foggy environment.

In addition to accuracy and stability requirements, continuous, real-time and simultaneous measurements at discrete points of a deteriorating structural system, as provided by monitoring, is required for efficient assessment of the performance of a structure. Conventional sensors have encountered substantial limitations in many crucial measurement operations. One may deploy a large number of structural monitoring sensors of various types at all critical locations in an infrastructure to gather structural information, but the cost of such a system can be extremely high. Therefore, the spatial resolution for measurements may be less than optimal due to the overall cost of the system. On the other hand, structural monitoring can be considered similar to quality assurance and acceptance sampling, and conventional sensors are not practical for continuously monitoring all performance indicators in all critical sections of an entire structural system.

The application of fiber-optic sensor technology to structural health monitoring (SHM) is still not widely accepted for transportation infrastructure monitoring although it has shown promise for such applications. Moreover, research and development in fiber-optic sensors seems to focus on measurements in strain, deformation, and temperature; other key structural parameter monitoring is still in need of research and development effort. In order to take full advantage of this technology, research and development efforts have to be directed into other parameter monitoring applications.

3. METHODOLOGY

A typical SHM system, as illustrated in Fig. 1, is composed of a network of sensors that measure the parameters related to the state of the structure and its environment. For transportation infrastructures such as bridges, overpasses and tunnels, the most important parameters are: positions, deformations, strains, pressures, accelerations and vibrations. In addition, chemical parameters such as humidity, pH value and chlorine concentration are equally as important as those physical parameters.

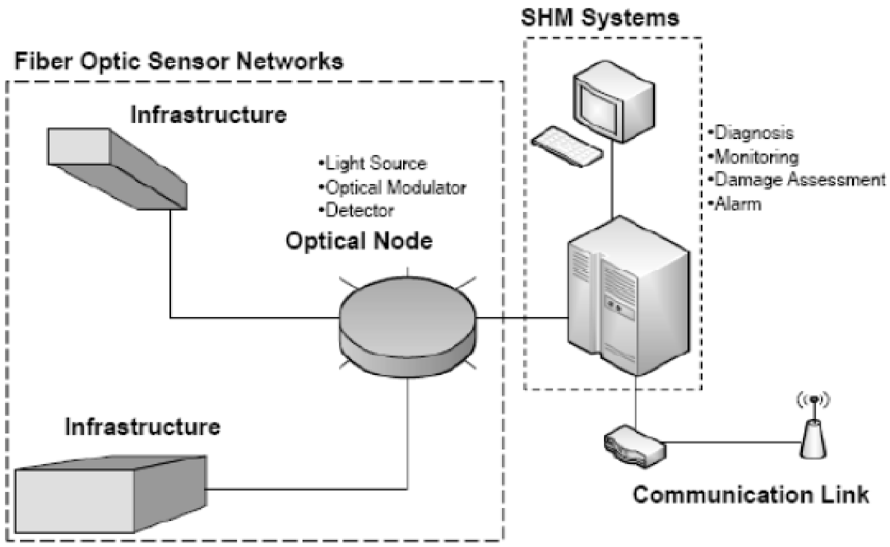

Fig. 1. Schematic of structural health monitoring and management system

Environmental factors often have substantial impact on the condition and operation of the transportation infrastructure. Those environmental parameters of interest are temperature, wind speed and direction, solar irradiation, precipitation, snow accumulation, water level and flow. The SHM system might be additionally equipped with a wireless network for remote monitoring, control and alarm for effective system operations.

To accomplish the project objective, we have performed a feasibility study and economic analysis for the proposed approach. The goal of the feasibility study primarily focuses on performance evaluation for various fiber-optic sensor technologies, the design and analysis of conceptual smart panels, multiplexing and networking of fiber-optic sensors, and performance analysis of conceptual TIHM systems. The result of the feasibility study will lead to a preliminary system configuration with projected functions and performances.

Economic analysis is also imperative for justifying the cost-effectiveness of the proposed approach. A first-step cost estimate will be based on the results of subject matter expert interviews, and hardware and material budgetary quotations. Additionally, alternative technologies having the potential for the same proposed purpose will be researched and evaluated for performance and cost-effectiveness comparisons.

4. TASK OVERVIEW

The focus of the research project is on the feasibility study of the proposed solution for monitoring and managing the health of transportation infrastructures. The project is composed of the five following tasks:

4.1 Literature search on infrastructure monitoring

Both graduate and undergraduate students will conduct a literature search and review publicly available databases as well as commercial sources for information about transportation infrastructure monitoring technologies. The conclusion of the literature search in conjunction with the results of expert interviews and field visits, and the findings from Task 2, will provide the necessary information regarding the present capability, cost, and limitation of monitoring systems. The literature search will also focus on the fiber-optic sensor technologies which will be considered for the transportation infrastructure monitoring systems. A variety of fiber-optic sensors are developed and some of them are commercially available. We plan to gather, review, and exploit all information obtained through the literature search to define the sensor performance requirements for the research project. The goal of the task is to establish the sensor performance requirements needed for the future project implementation.

4.2 Research the state of practice in bridge monitoring

In addition to the extensive literature search, research effort will then be directed to investigating the state of practice in bridge monitoring, an application that has received attention from many reviewers. Structure health monitoring includes two major functions: diagnosis, which includes the monitoring of the state of the whole infrastructure; and prognosis, which evaluates the evolution of damage, residual life, etc., of a structure.

The concept of fiber-optic smart structures for monitoring and managing the health of transportation infrastructures, such as bridges, is based on the use of an array of fiber-optic sensors that can monitor physical phenomenon closely related to structure damage. The sensor output signal makes diagnosis, usage monitoring, and prognosis possible in a continuous real-time domain. In practice, we need to identify key physical phenomena that can provide reliable measurements to effectively indicate to the design and maintenance teams the state of a bridge's health.

In this task, we will identify all physical phenomena which are vital to bridge health and usage monitoring. During this initial phase of research, appropriate fiber-optic sensors will be evaluated, sensor network and multiplexing technology will be studied, and bridge monitoring systems will be proposed based upon the state of practice.

4.3 Interview subject matter experts to obtain relevant field information

To accomplish Task 2, relevant field information is important to the success of the proposed research project. We plan to interview design and maintenance experts for field information. Preliminary information regarding the bridge monitoring system in terms of performance and operation are the main focuses. A design of a fiber-optic sensor network used for the bridge monitoring will be derived according to the field information and experts' inputs.

4.4 Development of fiber-optic sensor for bridge monitoring

The first step toward the development of fiber-optic sensors for bridge health monitoring will be the selection of a proper sensor for each key physical phenomenon measurement. The selection of a fiber-optic sensor will be based on its performance, cost effectiveness, and adaptability to the bridge monitoring system. Off-the-shelf fiber-optic sensors will be considered first to shorten the development time and ensure low nonrecurring cost as the monitoring system is developed and deployed. If special fiber-optic sensors are required to achieve the project goal, we are confident that the research group has the ability to develop the sensors that are required for the application of the bridge monitoring system. The principal investigator has extensive knowledge in the fiber-optic sensor area.

4.5 Development of design for sensor network prototype

Fiber-optic networks used in bridge structure monitoring may consist of different types of sensors for key physical phenomenon measurement; thus, technology in data fusion for the sensor network is required. In this task, we will make an attempt to design the sensor network based on the sensor selected from the previous task. Various sensor signal multiplexing/demultiplexing approaches will be evaluated and exploited for the sensor network. The result of this effort will provide the preliminary design and projected performance for the sensor network. A conceptual fiber-optic sensor network design will be presented to the transportation experts for critique and modifications will be implemented accordingly.

5. FIBER-OPTIC SENSORS

The research and development of fiber optic technology has inspired revolutionary changes to our lives today. Technological advances in fiber optics have paved the way for the widely deployed fiber optic communication networks, widely known as the information super highway. Today, we heavily rely on fiber-optic networks to transmit and receive data, voice and video signals via the internet [3,4].

Fiber-optic sensor technology may be considered an extension of the fiber -optic communication technology. It is commonly used in such applications as industrial automation, health care, aerospace and aviations. Compared to conventional sensor technology, fiber-optic sensors offer numerous advantages such as high sensitivity, all solid-state construction, no moving parts and a long lifetime.

In this section, we will explore several key fiber-optic sensors which are essential to the SHM applications. In addition to the advantages mentioned previously, fiber-optic sensors are capable of performing continuous, real-time structural parameter measurement which is impractical if we adapt conventional sensors [5]. All fiber-optic sensors considered for transportation infrastructural health monitoring are passive devices; thus no power system is required at the location of the structure. In an SHM system, optical fiber may also be used as a transmission medium to transport measured signals from optical fiber sensor networks which are deployed in the infrastructure; hence, remote monitoring is feasible.

From a broad perspective, applications of fiber-optic sensors in infrastructure health monitoring and management may be classified into two categories: 1) structural performance monitoring and 2) surveillance applications. While sensitivity requirements for performance monitoring sensors are typically medium-to-low for parameter measurement, surveillance sensors require ultra-high sensitivity to the measurement parameter. Performance monitoring sensors are typically used for: 1) monitoring the strain profile of large structures (e.g., a bridge or a ship hull), 2) monitoring and tracking crucial parameters (e.g., temperature, pressure, or acceleration) at crucial locations of a given system and 3) vibration monitoring for system identification and damage location. Since a majority of fiber sensors for performance monitoring relies on measuring the strain in the fiber, either directly in the case of strain sensing or indirectly in the case of fiber-optic transducers, we will address sensor requirements in terms of strain resolution. Resolution requirements for performance strain monitoring range from a few nε to tens of mε, depending upon the details of the application. Bandwidth requirements can vary from static (DC) to tens of kHz.

Surveillance sensors, on the other hand, are exploited for measuring very faint signals and require sensors with strain resolution on the order 10^{-13} to 10^{-14} and a frequency response from tens of Hz to tens of kHz. A good example of a high performance surveillance sensor is the fiber-optic hydrophone, used for underwater surveillance.[6] Strain resolution of the order of 10^{-14} is difficult to achieve with fiber Bragg grating and until recently surveillance sensors have been the exclusive realm of fiber interferometric sensors. However, fiber Bragg grating laser sensors (FBGLs) have recently demonstrated strain resolution of 10^{-14} [7], thus opening up the possibility of marking novel surveillance sensors.

The most common structural parameters that fiber-optic sensors measure are temperature, strain, pressure, deformation, vibration, and acceleration. The SHM system based on the fiber-optic sensor network may obtain structural parameter measurement of high sensitivity and accuracy for those parameters. In this section, we will provide a review for several major fiber-optic sensors to be used in the SHM applications.

5.1 Michelson Interferometer Sensors

The fiber-optic Michelson interferometer consists of a single-mode fiber directional coupler with reflection mirrors formed on the cleaved ends of both fibers on the same side of the coupler [8] as depicted in Fig. 2. As a sensor, one of the fibers is used as a reference fiber and the other is used to sense structural parameter. Any deformation in a transportation infrastructure will result in a change in the length difference of the two fibers. The interference between the two reflected light beams produces interference fringes. The shift of the fringe is an indirect measurement of the deformation strain.

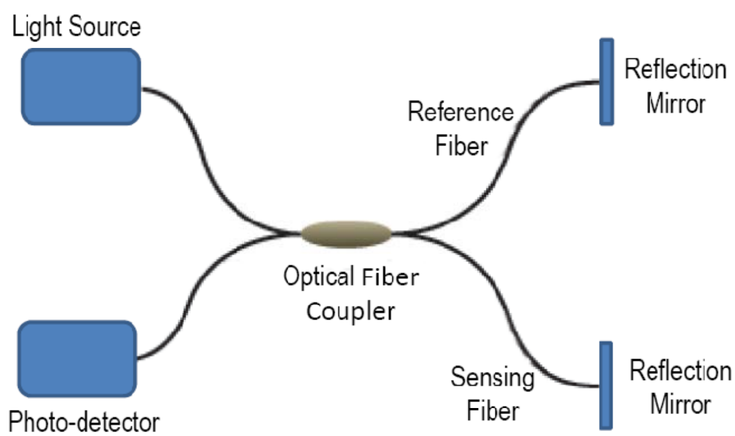

Fig. 2 Fiber-optic Michelson interferometer

To obtain accurate and reliable measurement of the deformation strain, a second mechanically scanning Michelson interferometer will be applied at the input/output port of the first fiber-optic interferometer to directly measure the length difference instead of the shift of the fringe pattern. The scanning Michelson interferometer is to create an optical path length difference such that it is equal to the length difference of the two fibers. Furthermore, a broadband light source or white light source having a low coherent length has to be used for the robust measurement. The scanning Michelson interferometer can accurately measure the optical path length difference by balancing the change of the length difference of the two fibers and hence yields the direct measurement deformation strain.

The fiber-optic sensor based upon Michelson interferometer is a long-gauge sensor for deformation strain measurement with a resolution in the range of micrometers.

It has excellent long term stability and is insensitive to the temperature. The schematic of the sensor for measuring structural deformation strain is illustrated in Fig. 3.

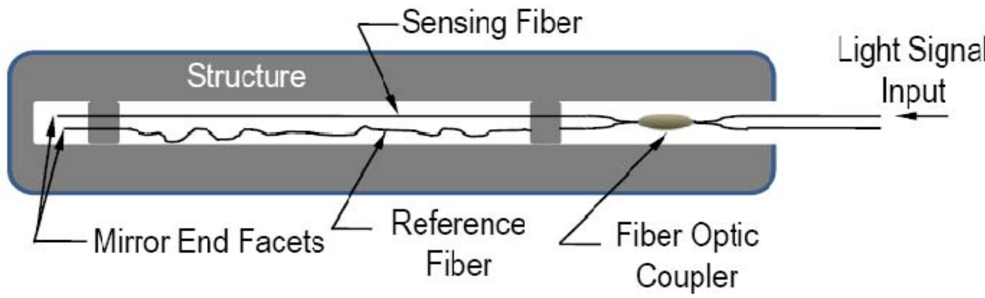

Fig. 3 A long-gauge deformation sensor using fiber-optic Michelson interferometer

5.2 Fiber Bragg Grating Sensors

Since the discovery of photosensitivity in optical fibers in 1978 by Ken Hill [9], and the subsequent demonstration of holographically-written gratings in fibers by Gerry Meltz [10], significant progress has been made towards the realization of various types of gratings in optical fibers. Advances in grating fabrication methods and fiber photosensitivity enhancement techniques have made it possible to fabricate a variety of index-modulated structures within the core of an optical fiber including Bragg grating [11], long period gratings [12], π-phase shifted grating[13], blazed or tilted gratings [14], and various types of chirped gratings [15].

Fiber grating devices have seen a wide variety of applications in both telecommunication and sensor fields. Fiber Bragg gratings (FBGs) have been routinely used with semiconductor lasers for producing a stable single frequency light signal with which an extreme broadband communication link may be realized. They will also play an important role in reconfigurable optical networks in the future optical network systems, since it is clear that grating-based devices are seeing great commercial success in the SHM applications. Transducers using FBGs such as pressure and acceleration sensors also have various applications and have now become commercially available. The requirements and designs of several reported grating-based transducers used in SHM applications will be discussed.

A fiber grating is made by periodically changing the refractive index in the glass core of the fiber. The refractive index changes are achieved by exposing the fiber to UV-light with a fixed pattern. The schematic of a fiber-optic grating is illustrated in Fig. 4. As the input light propagates through the grating having a period of Λ and the optical wavelength λ satisfies the Bragg condition, the maximum reflection occurs. The Bragg condition may be expressed as:

$$\lambda = 2n_{eff}\Lambda \tag{1}$$

where n_{eff} is the effective index of refraction of the optical fiber. The reflection and transmission spectra are shown in Fig. 5. Since n_{eff} is determined by the refractive index profit of the fiber, it changes with the variations of ambient temperature and external

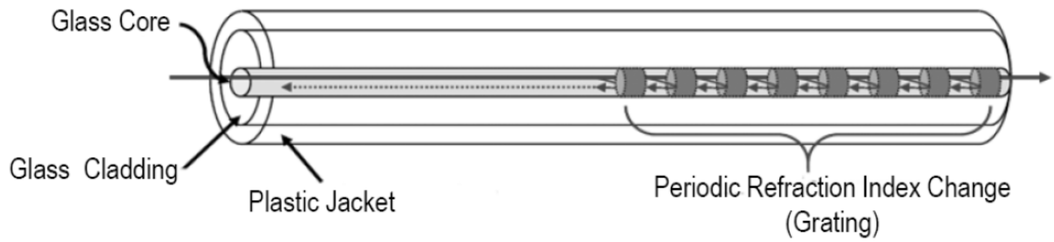

Fig. 4. Schematic of a fiber Bragg grating

mechanical stress. As the result, the center frequencies of the reflected and transmitted spectra will shift accordingly. Therefore, the measured frequency shift is an indication of the temperature and strain changes. FBGs can accurately measure local temperature and strain in a small region of the infrastructure with very high sensitivity.

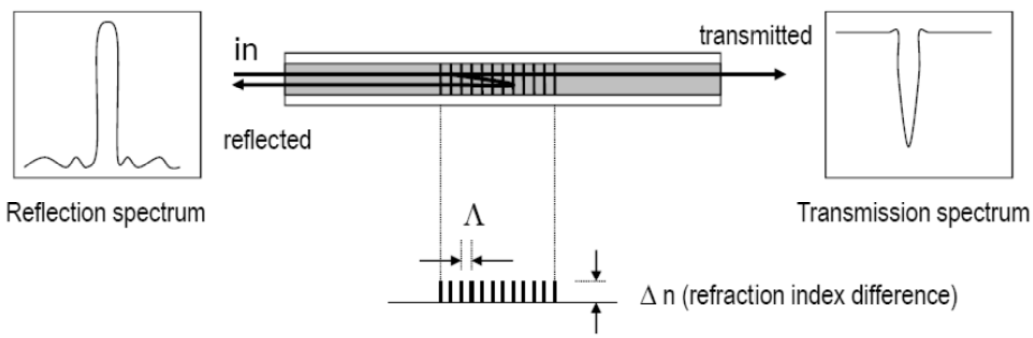

Fig. 5. Reflection and transmission spectra of a FBG

A summary of potential sensing applications of various types of fiber gratings is provided in Table 1. The table is not necessarily meant to be comprehensive and to cover all conceivable application areas in fiber grating sensors. Of course, there is no one ”magic” fiber-optic sensor which covers the full range of sensing requirements

Table 1: Summary of potential sensing applications of various types of fiber gratings

Grating Type	Applications
Fiber Bragg Grating (FBGs)	• Strain and temperature sensors • Pressure sensors • Acceleration sensors • Ultrasound sensors • Mechanical load sensors • Gas detection sensors • Extensometer • Electromagnetic field sensors • Reflection elements in interferometric sensor arrays
Fiber Bragg Grating Laser Sensors (FBGLs)	• Novel, compact hydrophones • Acoustic emission sensor for NDE
Long Period Gratings (LPGs)	• Bend sensors • Chemical sensors • Broadband source filters
Pi Phase Shifted Gratings	• Transverse load sensing
Chirp Gratings	• Strain sensing • FBG demodulation

for all applications. In this report we only briefly discuss FBG applications and examples from various field tests involving such sensors. Particular emphasis will be given to multiplexed networks based on FBGs for quasi-distributed measurements of parameters such as load, strain, temperature, and vibration. Observation has indicated that in certain cases the technology is fairly well developed and ready for widespread commercialization.

An array of FBGs has great potential for providing high performance structural sensing systems. Such measurements provide useful information regarding verification of novel construction approaches, infrastructure load rating systems and history of large loading events. Fig. 6 depicts the schematic of a distributed sensor array used for SHM systems. In fact, the distributed array of FBG sensors is a quasi-distributed sensor array, since the FBG sensor is a point sensor. This quasi-distributed senor array may be deployed over the entire transportation infrastructure to monitor strains and temperature at various locations. As previously discussed, this type of senor has very high resolution and accuracy of strain measurement--possibly on the order of $n\varepsilon$.

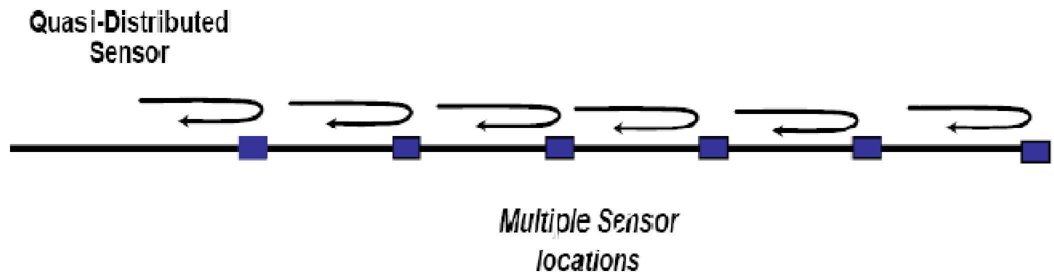

Fig. 6. Quasi-distributed sensor using an array of FBG sensors

Although the quasi-distributed FBG sensor has very good performance in strain measurement, it cannot distinguish strain and temperature as the effective index n_{eff} is dependent on both strain and temperature. Hence, a separated distributed temperature sensor is needed in order to extract the strain information for the system.

5.3 Distributed Fiber Sensors

Distributed fiber-optic sensors are important sensor technologies which may be used in the infrastructure health monitoring for large and long structures such as bridges, beams, and clamping ropes, from hundreds of meters to more than ten kilometers of length. Conventional sensor technology is often not feasible for the real-time and continuous structural parameters monitoring in these infrastructures.[16] Based on the light scattering in the optical fiber, the distributed fiber-optic sensor is capable of continuously monitoring major structural parameters and has high spatial resolution in the order of a few centimeters; hence, it allows structure engineers to measure structural parameters in an entire infrastructure system for design verification and damage and reliability assessments.

There are several methods available for extracting distributed strain and temperature information from optical fiber. These include techniques based on Rayleigh, Raman, and Brillouin scattering. Rayleigh scattering is the elastic scattering of light by particles much smaller than the wavelength of the light. It may occur when light wave travels in optical fiber in which the refractive index along the fiber fluctuates. Rayleigh light is scattered in all directions from the spatial variation of the refractive index along the optical fiber. The intensity of the scattered light at each location along the fiber is sensitive to both local strain and temperature. By measuring the back scattered light with a coherent signal detection method, one can readily extract the average strain and temperature information within a small segment of the fiber. Fiber-optic strain sensor having a gauge length of less than 0.5 m and a strain sensitivity of less than $n\varepsilon/\sqrt{Hz}$ at 2 kHz based on Rayleigh backscatter using a time division multiplexing (TDM) scheme has been demonstrated.[17] Sang et al.[18] present a technique based on measuring the spectral shift of the intrinsic Rayleigh backscatter signal along the optical fiber and converting the spectral shift to temperature. Using optical frequency domain reflectometry (OFDR) to record the coherent Rayleigh scatter pattern results in spatial resolution of around 1 cm and provides temperature measurement with an accuracy of 0.6 % of full scale temperature up to 850° C. Although a distributed stain and/or temperature sensor with small gauge length and high measurement accuracy may be obtained based on Rayleigh scattering, it requires a separate sensor to either calibrate temperature for measuring strain at a particular location or vice versa.

Raman- and Brillouin-scattering phenomena have been used for distributed sensing applications over the past few years. Whereas Raman scattering was first proposed for sensing applications in the 1980s, Brillouin-scattering was introduced for strain and/or temperature monitoring applications very recently. Both Raman- and Brillouin-scattering effects are associated with different dynamic inhomogeneities in the silica and, therefore, have completely different spectral characteristics.

Raman scattered light is caused by thermally activated molecular vibrations. Because the scattered light is generated by thermal agitation, one may expect a frequency shift from the incident light wave. As the incident light loses a slight amount of its energy to the molecules, this process, referred to Stokes scattering, leads to scattered light with lower optical frequency. On the other hand, light wave gains energy from the molecules it produces scattered light with a slightly higher frequency. This is referred to as anti-Stokes scattering. It is found that the amplitude of the anti-Stokes component is strongly temperature-dependent and that of the Stokes component is not. Hence, an optical signal processing technique utilizing Stokes and anti-Stokes components is needed to realize distributed temperature sensors. The magnitude of the anti-Stokes Raman scattering light is about one thousand times smaller (-30 dB) than that of the Rayleigh scattered light; multimode optical fiber is commonly exploited in the sensing system for improved scattered light capture. However, the attenuation coefficient of the multimode fiber is high; therefore, this technique limits the maximum measurement range to only 8 km.

Brillouin scattering results from the scattering of light by sound waves. Thermally excited acoustic waves (acoustic phonons) produce a periodic modulation of the refractive index. Brillouin scattering occurs when light is diffracted backward on this moving grating, giving rise to frequency shifted Stokes and anti-Stokes components. For intense light (e.g. laser light) travelling in an optical fiber, the variations in the electric field of the beam itself may produce acoustic vibrations in the medium via electrostriction. In a phenomenon known as stimulated Brillouin scattering (SBS), the beam may undergo Brillouin scattering from these vibrations, usually in a direction that is opposite to that of the incoming beam. The working principle of SBS may be schematically illustrated in Figure 7. The Brillouin frequency shift attributed to the strain and temperature may be expressed as:

$$\upsilon_B = \upsilon_{Bo} + B_T(T - T_o) + B_s(\varepsilon - \varepsilon_o) \quad (2)$$

where ν_{Bo} and ν_B is the peak frequency of the SBS for unstrained and strained fibers, respectively. In equation (2), B_T and B_S are Brillouin thermal and strain coefficiencies.

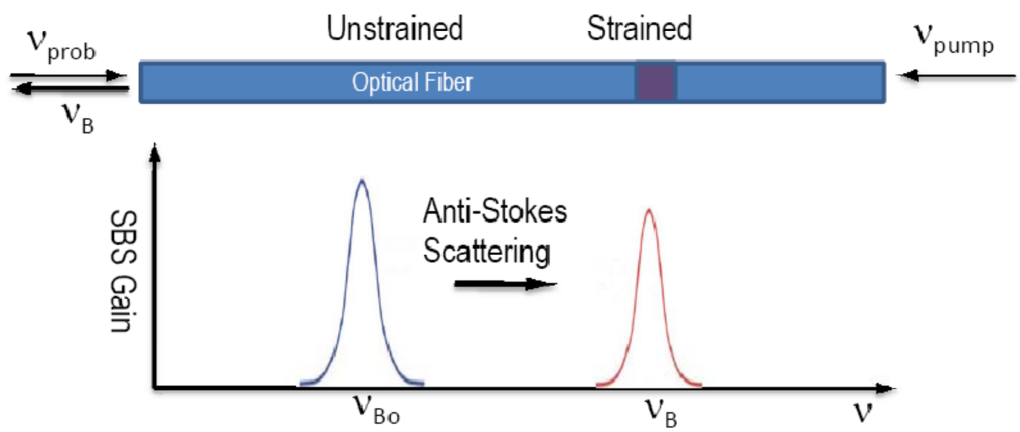

Fig. 7. Stimulated Brillouin Scattering in single mode optical fiber

The distributed sensor based on SBS is most suited for SHM applications. The distributed optical fiber Brillouin sensor based on the SBS has been investigated for pipeline buckling and concrete/FRP column monitoring [19]. Using a coherent detection scheme, the SBS-based sensor offers several advantages, including long measured length, high resolution and accuracy, and stability. The most important feature of the SBS-based Brillouin distributed sensor is its ability to measure strain and temperature separately or simultaneously with high spatial resolution and accuracy.

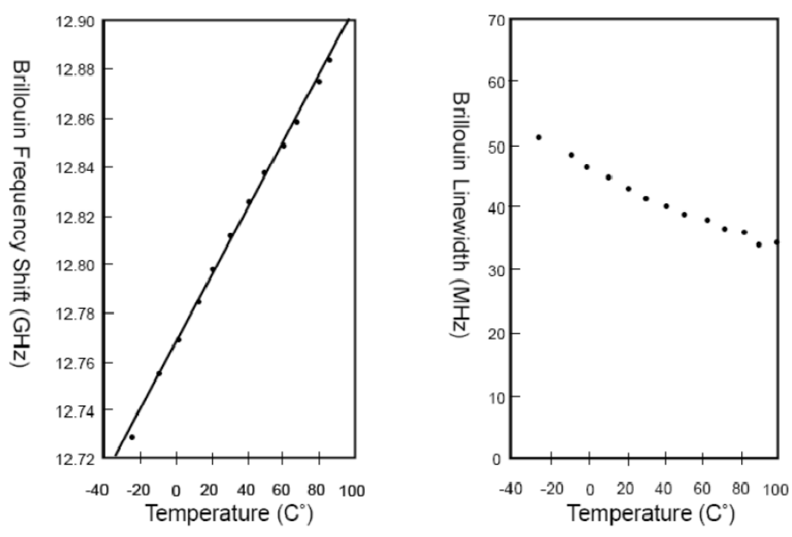

Fig. 8 Temperature characteristics of SBS distributed sensors

Figure 8[20] shows the experiment results of the temperature characteristics of the SBS distributed sensor. The Brillouin frequency shift in an order of tens of GHz exhibits a fairly linear relation with the measure temperature as in Figure 8 (a). Conversely, as can be seen in Figure 8 (b), the Brillouin linewidth decreases when the measured temperature increases. The experimental results in Figure 9 (a) show that the Brillouin frequency shift also linearly depends on the fiber elongation which is the indication of the local strain; however, the linewidth is independent of the elongation, as shown in Figure 9 (b). These measurements conclude that the temperature and strain may be measured separately based on Brillouin frequency shift and linewidth variation.

The Brillouin distributed sensor technology allows fast measurement of strain and temperature to be achieved within a few seconds, owing to the use of straightforward optical signal processing technique. Furthermore, the monitoring system may incorporate an optical amplifier to boost up the optical power to extend the measurement range; this makes the Brillouin distributed sensor a practical choice for the transportation infrastructure monitoring system.

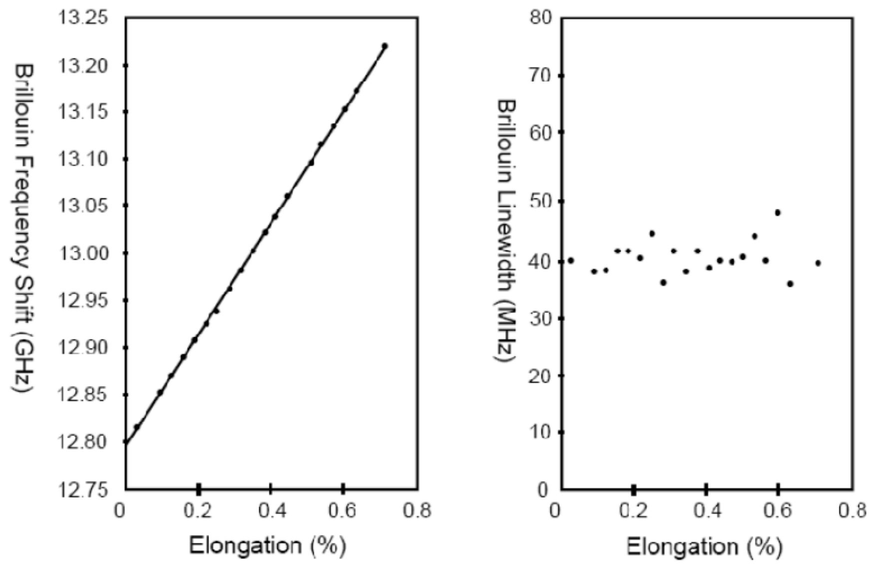

Fig. 9 Spectrum characteristics of SBS distributed sensors

6. RESULTS

The results of the literature search, research of the state of practice in bridge monitoring, and interview subject matter experts are reported. In addition, the status quo for the transportation SHM systems is presented in the report. Most of this information is based on case studies and reflects the status quo of the technology and applications; they will be valuable for the future research in the transportation SHM systems.

6.1 Michelson interferometer sensors

The Michelson interferometer sensors may be employed as long gauge sensors for static or dynamic measurement. The deformation resolution of 2 μm and 0.01 μm is obtained for static and dynamic deformation measurement, respectively. For the static deformation measurement, the long gauge has shown very good long term stability over six years. For the practical application, long gauges have been deployed in the Bolshoi

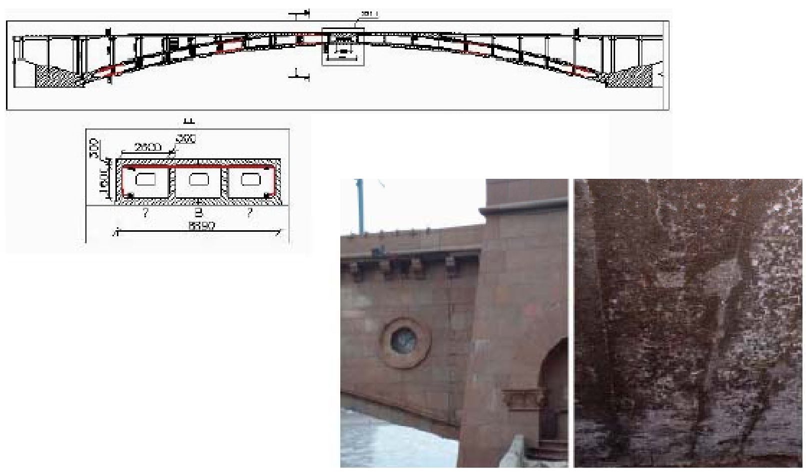

Fig. 10 Long gauge deformation sensors for monitoring Bolshoi Moskvoretskiy Bridge
Data source: Roctest, Inc.

Moskvoretskiy Bridge, which is a historic 70-year-old bridge, to obtain knowledge about structural behavior and follow the evolution of degradations, as shown in Fig. 10. The long gauge deformation sensors are used to perform continuous static monitoring.

In Fig. 11, deformation and temperature data of continuous static monitoring during a period of four days is provided.

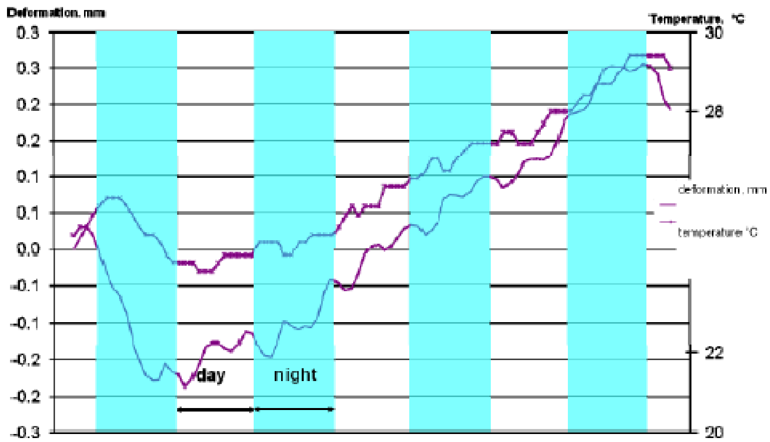

Fig. 11 Deformation and temperature monitoring for Bolshoi Moskvoretskiy Bridge
Data source: Roctest, Inc.

6.2 Fiber optic Bragg grating sensors

In 1998 the historic Horsetail Fall Bridge was strengthened via composite FRP overwrap. During the strengthening work, 26 strain gauges based upon fiber-optic Bragg grating sensors were installed for static and dynamic strain monitoring. A typical measurement result for dynamic monitoring is given in Fig. 12.

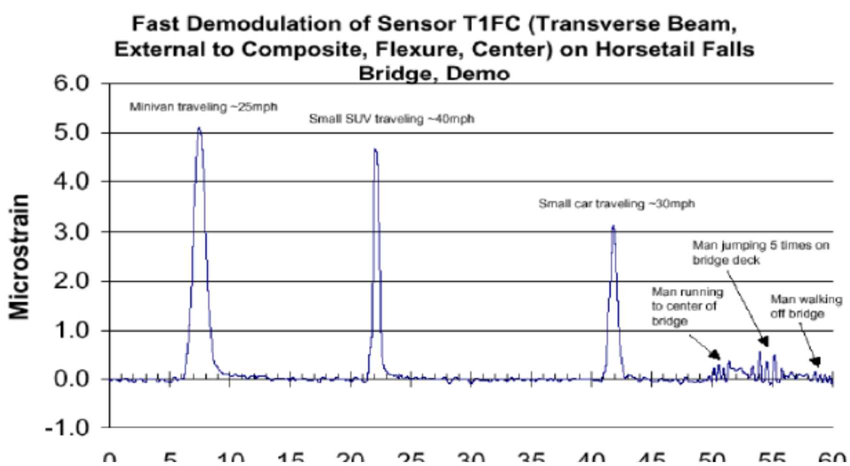

Fig. 12 FBG sensors for dynamic strain monitoring
Data source: Roctest, Inc.

6.3 Distributed fiber sensors

The distributed fiber sensor is a relatively new technology compared with point sensors, and is still in the research and development stage. Field demonstrations of distributed fiber sensors for monitoring construction and structural status for dam and gas pipelines are ongoing, but the results are very limited. It also used for monitoring and predicting landslides from dangerous slopes. According to the preliminary results from the field tests, the distributed fiber sensor may play an important role in the SHM systems.

A distributed Brillouin sensing system was installed to monitor strain as well as temperature distribution of a gas pipeline. The abnormal strain could be induced by landslide and temperature distribution along the pipe may be used to detect gas leaks. The purpose of the monitoring would be to identify problem areas and the optimum excavation schedule for releasing strain. Fig. 13 shows the strain distribution along the entire pipeline system.

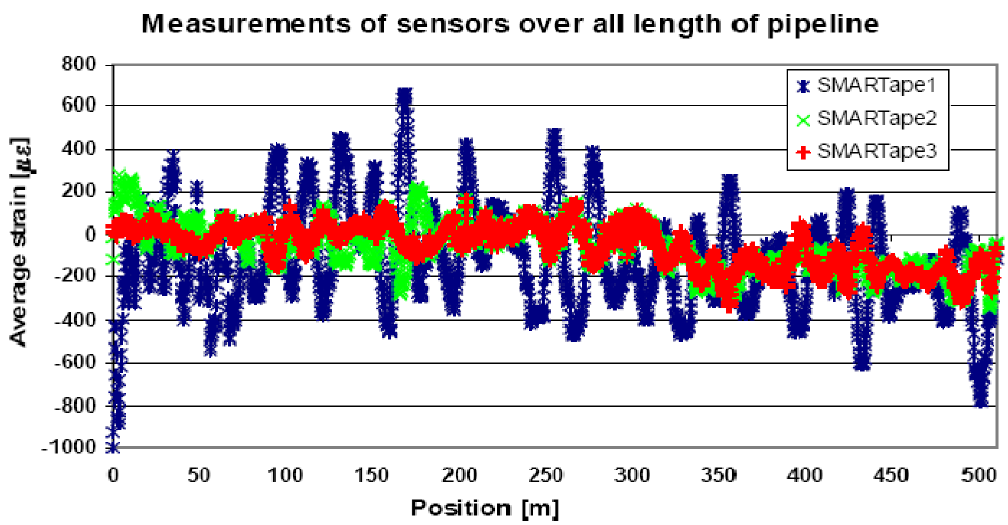

Fig. 13 Brillouin distribution sensing system for gas pipe line strain and temperature

Data source: Roctest, Inc.

7. CONCLUSION AND FUTURE PLAN

The majority of the structural monitoring sensors used in long span bridge health monitoring systems are still those based on conventional transducer technology. The Akashi Kaikyo Bridge in Japan, the world's longest suspension bridge, uses seismometer, anemometer, accelerometer, velocity gauge, Global Positioning System (GPS), girder edge displacement gauge, Tuned Mass Damper (TMD) displacement gauge and thermometer for dynamic monitoring [21]. Significant progress in the development of fiber optic sensors and wireless sensors has been made in the past decade and some of them are now commercially available. Whereas fiber-optic sensors have successfully been applied for the long term SHM of large scale bridges such as the Confederation Bridge[22] and the Tsing Ma Bridge[23], wireless sensors for the bridge SHM application are still in the technology demonstration stage.

Some conventional sensors currently used in long span bridge health monitoring are deficient in providing adequate accuracy and long-term stability. For example, a GPS used in the Akashi Kaikyo Bridge for absolute displacement or deflection monitoring has three limitations: 1) the measurement accuracy of a GPS is not sufficient for meeting bridge health monitoring requirements; 2) a GPS does not work well for monitoring the displacement of piers beneath the bridge deck (caused by ships colliding and settlement) and 3) a GPS is not capable of accurately measuring deflection in a foggy environment. A long gauge deformation sensor using the previously discussed fiber-optic Michelson interferometer becomes an ideal choice for the application because of its long-term stability and capability of measuring the absolute displacement.

Fiber optic sensors such as FBG and SBS sensors are only applied to the measurement of strain and temperature with high sensitivity and accuracy; one may be used to implement a quasi-distributed sensor network and the other is a distributed sensor. Fiber -optic sensors have the additional advantages of low bias drift and high frequency response in addition to those mentioned early. Electrical gauges for strain and vibration monitoring normally encounter technical problems in either bias stability and/or dynamic response where fiber-optic sensors may be the solution.

Fiber-optic sensor technology for the SHM application is still not widely accepted for transportation infrastructure monitoring. Research and development in fiber-optic sensors seems to focus on measurements in strain, deformation and temperature; other key structural parameter monitoring is still lacking research and development effort. In order to take full advantage of the technology, a research and development effort has to be directed into other parameter monitoring applications.

In future research, validation of the point and distributed fiber-optic sensors will be implemented through laboratory and field tests. A structure health monitoring system using a quasi-distributed sensor network and distributed sensor will then be designed, built, and tested for field deployment test. Complete testing for the designed sensing network will be performed in the Civil Engineering laboratory of California State University, Long Beach to qualify the prototype design. The research team has made a preliminary arrangement with Caltrans engineers to conduct field deployment tests in a transportation infrastructure in Southern California. The field test data will be reviewed and analyzed to gather important information to justify fiber-optic sensing technology for future systems. The prototype deployed in the selected transportation infrastructure will continue to collect structural information for technology and design validation. A design for fiber-optic sensor networks to be used in the monitoring and management system for transportation infrastructures based on the research project will be proposed as the end result of the research effort.

8. IMPLEMENTATION

The results of this research project are based on literature surveys, expert interviews, and vendor product brochures of fiber-optic sensors for infrastructure health monitoring applications and cannot be implemented directly. Rather, the results of this report provide comprehensive information regarding feasibility of the implementation of the transportation SHM based on fiber-optic sensors. The most significant finding of this research is that, despite that fact that the application of fiber-optic sensors in the transportation SHM is far from being mature; the potential cost benefit of the fiber optic sensor system for the transportation SHM is tremendous. Additional research in the development of fiber-optic sensors and system architecture for the transportation SHM will necessary for the deployment of the transportation SHM systems.

9. REFERENCES

1. Arnoldy, B., 2007. How to pay for US road and bridge repair? The Christian Science Monitor, August 10.
2. J Johnson, E. A., 2003. Innovative Bridge Structural Health Monitoring Using Variable Stiffness and Damping Devices. Metrans Research Project, Project Number 03-17.
3. Brackett, C. A., editor, 1989. IEEE Communication Magazine: Special Issue on Lightwave Systems and Components, vol. 27.
4. Barry, R. A., editor, 1996. IEEE Network: Special Issue on Optical Networks, vol. 10.
5. Frangopol, D. M., Strauss, A., and Kim, S., 2008. Bridge Reliability Assessment Based on Monitoring. ASCE Journal of Bridge Engineering, pp. 258-270.
6. Davis, A. R., Kirkendall, C. K., Dandridge, A., and Kersey, A. D., 1997. 64 channel all optical deployable acoustic arrays. Proc. 12th Conf. Optical Fibre Sensors, pp. 616.
7. Koo, K. P. and Kersey, A.D., 1995. Bragg grating based laser sensor systems with interferometric interrogation and wavelength division multiplexing, Journal of Lightwave Technology**,** vol. 13, pp. 1243-1249.
8. Kashyap, R. and Nayar, B. K., 1983. An All Single-Mode Fiber Michelson Interferometer Sensor. Jouranl of Lightwave Technology, vo. l1, pp. 619-624.
9. Hill, K. O., Fujii,Y., Johnson, D. C. and. Kawasaki, B. S., 1978. Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication. Appl. Phys. Lett., vol. 32, pp, 647-649.
10. Meltz, G., Morey, W. W., and Glenn, W. H., 1989. Formation of Bragg gratings in optical fibers by a transverse holographic method. Optics. Lett., vol. 14, pp. 823-825.
11. Miguel, J. (2002). Handbook of Optical Fiber Sensing Technology.
12. Vengsarkar, A. M., Lemaire, P. J., Judkins, J. B., Bhatia, V., Erdogan, T., Sipe, J. E., 1996. Long-period fiber gratings as band-rejection filters. Journal Lightwave Technology, vol. 14, pp. 58-65.
13. Canning, J., and Seats, M.G., 1994. π-phase shifted periodic distributed structures in optical UV post processing. Electron. Lett., vol. 30, pp. 1344-1345.
14. Erdogan, T. and Sipe, J., 1995. Radiation mode coupling loss in tilted fiber phase grating. Optics Lett. vol. 20, pp. 1838-1840.
15. Byron, K., Sugden, K., Bircheno, T. and Bennion, I., 1993. Fabrication of chirped Bragg gratings in photosensitive fibers. Electron. Lett., vol. 29, pp. 1659-1660.
16. Frangopol, D. M., Strauss, A., and Kim, S., 2008. Bridge Reliability Assessment Based on Monitoring. ASCE Journal of Bridge Engineering, pp. 258-270.

17. Posey Jr., R., Johnson, G .A., and Vohra, S.T., 2000. Strain sensing based on coherent Rayleigh scattering in an optical fibre. Electron. Lett., vol. 36, pp. 1688-1689.

18. Sang, A. K., Froggatt, M. E., Gifford, D. K., Kreger, S. T., and Dickerson, B. D., 2008. One Centimeter Spatial Resolution Temperature Measurements in a Nuclear Reactor Using Rayleigh Scatter in Optical Fiber. IEEE Sensors Journal, vol. 8, pp. 1375-1380.

19. Bao, X., Ravet, F., and Zou, L., 2006. Distributed Brillouin Sensor Based on Brillouin Scattering for Structural Health Monitoring. Optical Fiber Communication Conference, 2006 and the 2006 National Fiber Optic Engineers Conference.

20. Nikle`s, M., Th´evenaz, L. and Robert, P. A., 1997. Brillouin Gain Spectrum Characterization in Single-Mode Optical Fibers. Journal of Lightwave Technology, vol. 15, pp. 1843-1851.

21. Sumitro, S., Matsui, Y., Kono, M., Okamoto, T. and Fujii, K., 2001. Long span bridge health monitoring system in Japan. Proceedings of SPIE, vol. 4337, pp. 517-524.

22. Cheung, M. S., Tadros, G. S., Brown, T., Dilger, W. H., Ghali, A., and Lua, D. T., 1997. Field monitoring and research on performance of the Confederation Bridge. Canadian Journal of Civil Engineering, vol. 26, pp. 951-962.

23. Lau, C. K., Mak, W. P. N., Wong, K. Y., Chan, W. Y. K., and Man, K. L. D., 1999. Structural health monitoring of three cable-supported bridges in Hong Kong. F. K. Chang, editor. Structural health monitoring. Lancaster (PA), Technomic; pp 450-460.