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A Review: An Analysis of Fiber Bragg Grating For Dispersion Compensation in Optical Fiber Communication System

Srashti Kamthan
M.Tech. Scholar in Digital Communication and Engineering
VIT University, Near Katpadi Rd, Vellore, Tamil Nadu 632014, India
E-Mail: srashtiK25@gmail.com

ABSTRACT

The benefits of Fiber Bragg Gratings make them attractive to other applications as well. In telecommunications systems, they are used for dispersion compensation in fiber optic transmission systems, de-multiplexing filters for wavelength division multiplexing systems, and long-period gratings for gain flattening of erbium-doped fiber amplifiers. The primary application of Fiber Bragg Gratings is in optical communications systems [1]. They are specifically used as notch filters. They are also used in optical multiplexers and de-multiplexers with an optical circulator, or Optical Add-Drop Multiplexer (OADM).

Keywords: Fiber, Optical, OADM, FGB, Division, Multiplexing.

1. INTRODUCTION

The demand for more bandwidth in telecommunication networks has rapidly increased the development of new optical components and device. Fiber Bragg Gratings have been vital in the phenomenal growth of some of these products and are recognized as one of the most significant enabling technologies for fiber optic communications in the last decade [2],[3]. A de-multiplexer can be achieved by cascading multiple drop sections of the OADM, where each drop element uses a FBG set to the wavelength to be de-multiplexed. Conversely, a multiplexer can be achieved by cascading multiple add sections of the OADM. FBG de-multiplexers and OADMs can also be tunable.

2. Motivation and Overview

The demand for more bandwidth in telecommunication networks has rapidly increased the development of new optical components and device. Current efforts of research and development are aiming at increasing the total capacity of optical fibers as a medium and improving long haul optical transmission systems using new innovative technologies such as ultra-dense wavelength division multiplexing (WDM. The advances in the optical communications have been synergized by development of efficient and powerful optical components which eliminate the need of costly conversions from optical to electrical signal and back.

Fiber Bragg Gratings have been vital in the phenomenal growth of some of these products and are recognized as one of the most significant enabling technologies for fiber optic communications in the last decade. Since their market introduction in 1995to 2014, the use of optical Fiber Bragg Gratings in commercial products has grown exponentially, largely in the fields of telecommunications and stress sensors [4].

Fiber-optic sensors are generally used for several types of applications. In smart manufacturing they are attached or embedded in components, typically composites, during the manufacturing process and used to monitor such things as temperature, pressure, viscosity, degree of cure or residual strain. During service, Fiber Bragg Grating sensors may be used for non-destructive evaluation (NDE) to measure strain profiles, monitor de-lamination or other changes in structural characteristics. They may also be used in health monitoring and damage assessment of structures, or to support control systems by responding to changes in the environment [5]. Being EMI/RFI immune, flexible and compact fiber-optic sensors based on Bragg gratings have found applications in a wide variety of industries.

In engineering, FBG sensors have been used in mining and to monitor tunnels, bridges and dams. In the nuclear industry they have been used for containment shells, cooling towers, steam pipes and storage sites and in marine engineering for masts, lock gates and undersea acoustic monitors [6]. They have found particular application in aerospace, especially for composite materials where they are used for structural health monitoring, impact detection, cure processing, and shape control and vibration damping. Their use is also being considered in biomedical engineering where, for example, monitoring of mechanical performance and damage in artificial limbs is extremely important for orthopedic applications [7].

Another application for these gratings is wavelength stabilization of lasers, which means control of a laser's wavelength and possibly enforcement of single-axial-mode lasing. Fiber Bragg Gratings are attractive devices for this application because they are easy to make and offer precise control of the center wavelength, excellent temperature stability and tenability. These benefits can significantly improve the performance and capabilities of diode lasers and fiber lasers.

The benefits of Fiber Bragg Gratings make them attractive to other applications as well. In telecommunications systems, they are used for dispersion compensation in fiber optic transmission systems [8], de-multiplexing filters for wavelength division multiplexing systems, and long-period gratings for gain flattening of erbium-doped fiber amplifiers. They are also stimulating growth in fiber optic applications outside of telecommunications, such as nonlinear frequency conversion, spectroscopy, and remote sensing.

The primary application of Fiber Bragg Gratings is in optical communications systems. They are specifically used as notch filters. They are also used in optical multiplexers and de-multiplexers with an optical circulator, or Optical Add-Drop Multiplexer (OADM).

A de-multiplexer can be achieved by cascading multiple drop sections of the OADM, where each drop element uses a FBG set to the wavelength to be de-multiplexed. Conversely, a multiplexer can be achieved by cascading multiple add sections of the OADM. FBG de-multiplexers and OADMs can also be tunable [9]. In a tunable de-multiplexer or OADM, the Bragg wavelength of the FBG can be tuned by strain applied by a piezoelectric transducer. The main advantage is that in these applications since Fiber Bragg Grating can be incorporated in the optical fiber itself there is no need to insert lossy couplings in the form of connectors or to make costly conversions from optical to electrical domain and back. Similarly in the field of Fiber Optic Sensors FBGs find many applications since here also the Optical sensor is integrated in Optical Fiber itself.

3. Objective

- To simulate Fiber Bragg Gratings and validate results using theoretical and experimental work.
- To study wavelength shift in Fiber Bragg Gratings on simulated external perturbation using a wideband source.
- To design Fiber Bragg Grating Interrogator for Fiber Communication systems.
- To Dispersion Compensation in Optical Fiber Communication System.

4. Problem Statement

- Extensive literature survey has been conducted to study the literature available in the field of Fiber Bragg Gratings, their production techniques, characterization and simulation.
- There is a need to study Wavelength Shift by simulating external perturbation to the Fiber Bragg Grating.
- Model has to be constructed and then coding for the simulation is required.
- Iterations have to be performed and the results have to be validated against practical experimental work to fine tune the simulation.

5. Contribution In Of Optical Communications System

The primary application of Fiber Bragg Gratings is in optical communications systems. They are specifically used as notch filters. They are also used in optical multiplexers and de-multiplexers with an optical circulator, or Optical Add-Drop Multiplexer (OADM). A de-multiplexer can be achieved by cascading multiple drop sections of the OADM [10], where each drop element uses a FBG set to the wavelength to be de-multiplexed. Conversely, a multiplexer can be achieved by cascading multiple add sections of the OADM. FBG de-multiplexers and OADMs can also be tunable. In a tunable de-multiplexer or OADM, the Bragg wavelength of the FBG can be tuned by strain applied by a piezoelectric transducer. The sensitivity of a FBG to strain is discussed below in Fiber Bragg Grating sensors.

5.1. Contribution In of Fiber Bragg Grating

As well as being sensitive to strain, the Bragg wavelength is also sensitive to temperature. This means that Fiber Bragg Gratings can be used as sensing elements in optical fiber sensors [7]. In a FBG sensor, the measure and causes a shift in the Bragg wavelength, $\Delta\lambda B$. The relative shift in the Bragg wavelength, $\Delta\lambda B / \lambda B$, due to an applied strain (ε) and a change in temperature (ΔT) is approximately given by:

$$\left[\frac{\Delta\lambda_B}{\lambda}\right] = C_{S\epsilon} + C_T\,\Delta T \quad\ldots\ldots\ldots\ldots\ldots\ldots 1.1$$

$$\left[\frac{\Delta\lambda_B}{\lambda}\right] = (1 - C_\varepsilon)\epsilon + \alpha_\Lambda + \alpha_n)\Delta T \quad\ldots\ldots\ldots 1.2$$

Here, C_S is the coefficient of strain, which is related to the strain optic coefficient $\mathbf{p_e}$. Also, CT is the coefficient of temperature, which is made up of the thermal expansion coefficient of the optical fiber $\boldsymbol{\alpha}_{\Lambda}$, and the thermo-optic coefficient $\boldsymbol{\alpha_n}$.

Fiber Bragg Gratings can then be used as direct sensing elements for strain and temperature. They can also be used as transduction elements, converting the output of another sensor, which generates a strain or temperature change from the measure and, for example Fiber Bragg Grating gas sensors use an absorbent coating, which in the presence of a gas expands generating a strain, which is measurable by the grating. Technically, the absorbent material is the sensing element, converting the amount of gas to a strain. The Bragg grating then transducers the strain to the change in wavelength.

Specifically, Fiber Bragg Gratings are finding uses in instrumentation applications such as seismology, and as down whole sensors in oil and gas wells for measurement of the effects of external pressure, temperature, seismic vibrations and inline flow measurement. As such they offer a significant advantage over traditional electronic gauges used for these applications in that they are less sensitive to vibration or heat and consequently are far more reliable [11]. The Fiber Bragg Gratings can be used for measuring strain and temperature in composite materials for aircraft and helicopter structures. The Fiber Bragg Grating has to be interrogated in order to provide any sensor application. This thesis deals with not only the simulation of Fiber Bragg Gratings for application in communications and sensor systems abut also gives the design of low cost fiber optic interrogator for achieving this. The design of fiber optic interrogator is further upgraded to mitigate the effect of micro bending losses caused in the optical fiber connecting the instrument to the sensor.

6. Literature Survey

The formation of permanent gratings in an optical fiber was first demonstrated by Kenneth O Hill in 1978 at the Canadian Communications Research Centre (CRC), Ottawa, Canada. They launched intense Argon-ion laser radiation into a germania-doped fiber and observed that after several minutes an increase in the reflected light intensity occurred which grew until almost all the light was reflected from the fiber. Spectral measurements, done indirectly by strain and temperature tuning of the fiber grating, confirmed that a very narrowband Bragg grating filter had been formed over the entire 1-m length of fiber. This achievement, subsequently called Hill gratings, was an outgrowth of research on the nonlinear properties of germania-doped silica fiber. It established an unknown photosensitivity of Germania fiber, which prompted other inquires, several years later, into the cause of the fiber photo-induced refractivity and its dependence on the wavelength of the light which was used to the form the gratings.

Detailed studies showed that the grating strength increased as the square of the light intensity, suggesting a two-photon process as the mechanism. In the original experiments, laser radiation at 488 nm was reflected from the fiber end producing a standing wave pattern that formed the grating. A single photon at one-half this wavelength, namely at 244 nm in the ultraviolet, proved to be far more effective.

Meltz *et al*. [2008] showed that this radiation could be used to form gratings that would reflect any wavelength by illuminating the fiber through the side of the cladding with two intersecting beams of UV light; now, the period of the interference maxima and the index change was set by the angle between the beams and the UV wavelength rather than by the visible radiation which was launched into the fiber core. Moreover, the grating formation was found to be orders-of-magnitude more efficient.

At first, the observation of photo-induced refractivity in fibers was only a scientific curiosity, but over time it has become the basis for a technology that now has a broad and important role in optical communications and sensor systems. Research into the underlying mechanisms of fiber photosensitivity and its uses is on-going in many universities and industrial laboratories in Europe, North and South America, Asia, and Australia. Several hundred photosensitivity and fiber grating related articles have appeared in the scientific literature and in the proceedings of topical conferences, workshops, and symposia. FBGs are now commercially available and they have found key applications in routing, filtering, control, and amplification of optical signals in the next generation of high-capacity WDM telecommunication networks.

Kenneth *et al* [2008] highlighted the salient properties of periodic, optical waveguide structures that are used in the design of grating filters and gave an overview of their key applications in optical telecommunications and quasi distributed thermo physical measurement systems. Other articles and reviews of the technology that have appeared include a recent comprehensive article by Bennion *et al* [2008]. and survey papers that discuss the physical mechanisms that are believed to be important in photosensitivity and applications of gratings to fiber optic sensors. Subhash *et al*. and Kashyap *et al* [2008] demonstrated the use of multiple blazed gratings to flatten the gain spectrum of erbium-doped fiber amplifiers. Eggleton *et al* [2008] demonstrated dispersion compensation by pulse compression with the use of a chirped grating.

Chtcherbakov *et al* [2008] presented a chirped grating interrogator for Fiber Bragg Grating sensors. The interrogator uses the wavelength dependence of the phase group-delay response of a chirped Fiber Bragg Grating to determine the Bragg wavelength of the sensor. The sensitivity of the interrogator is determined by the selection of the grating length and the bandwidth. The experimental results demonstrated strain measurements over wide range per meter. It was also proposed by Chtcherbakov that multiplexing can be achieved by using an arrayed-waveguide grating that allows the interrogation of more than one grating sensor with a single chirped grating.

Lloyd *et al* [2009] reported the first resonant-cavity time-division-multiplexed (TDM) Fiber Bragg Grating sensor interrogation system. This novel design uses a pulsed semiconductor optical amplifier in a cyclic manner to function as the optical source, amplifier, and modulator. Compatible with a range of standard wavelength detection techniques, this optically gated TDM system allows interrogation of low reflectivity commodity sensors spaced just 2 m apart, using a single active component. Results demonstrate an exceptional optical signal-to-noise ratio of 36 dB, a peak signal power of over +7 dBm, and no measurable crosstalk between sensors. Temperature tuning showed that the system was fully stable with a highly linear response.

Sano *et al* [2009] gave a new type of interrogator for distributed Fiber Bragg Grating (FBG) sensors that employs an arrayed waveguide grating (AWG) and presented its operating features in detail investigated both theoretically and experimentally. The remedy for achieving the linear characteristics of wavelength detection as well as for insuring the reliable and environmentally stable operation of interrogation were also proposed and its usefulness demonstrated in good agreement with the experimental results. The developed interrogator consisted of a fully passive, small, all-solid, rugged optical IC and could detect wavelengths.

Chtcherbakov *et al* [2009] reported a chirped Bragg grating interrogator for a uniform Bragg grating sensor. The wavelength of light reflected by the sensing grating is a function of strain. The position within the chirped Bragg gating the light is reflected from is a function of its wavelength. This position is determined by amplitude modulating the light source and measuring the phase of the reflected light and thus determining the value of the strain .

Geiger *et al* [2009] gave a new technique for the interrogation of in-Fiber Bragg Grating sensors using an acousto-optic tunable filter (AOTF). The scheme involved frequency shift keying (FSK) of the RF drive to the AOTF to track the wavelength shifts of a Bragg grating. Experimental results were presented for temperature measurement. This technique provided a frequency-agile system, capable of rapid, random access and very wide tuning range.

Foote *et al* [2009] presented work which indicated that the use of embedded Fiber Bragg Gratings as optical sensors for smart sensory structures could be a viable technology. It has been demonstrated that gratings can be embedded routinely without damage into carbon fiber composite material. The harsh embedding conditions do not significantly affect the optical characteristics of the gratings. Once embedded, the gratings act as strain sensors producing measurements consistent with predictions. In this work six embedded, multiplexed grating sensors detected strain gradients in a loaded composite panel of complex structure.

Patrick *et al* [2009] demonstrated a novel sensor which used the difference in strain and temperature response of Fiber Bragg Gratings and a long period fiber grating to discriminate between strain and temperature induced wavelength shifts. Sensor interrogation was performed entirely on the Fiber Bragg Grating reflection signals. Strain and temperature were simultaneously measured to ±9 μstrain and ±1.5°C .

Berkoff *et al* [2009] described a multiplexing approach for high-resolution sensing with Bragg gratings. The scheme used a band-pass wavelength division multiplexer to separate the returned wavelengths from an array of gratings, and interferometric processing to attain high-strain resolution. A strain resolution of 1.5 nano-strains was demonstrated, with a sensor bandwidth of 10 Hz-2 kHz for four sensors.

Davis *et al* [2010] reported the demonstration of an instrumentation system capable of monitoring a large number of Bragg gratings using a common source and scanning narrowband filter. The system described monitored five arrays of 12 Bragg gratings sensors for a total of 60 sensor elements with μ strain resolution.

Ferreira *et al* [2010] presented a pseudo heterodyne, open-loop demodulation technique for detecting wavelength shifts in wavelength encoded Fiber Bragg Grating sensors. The scheme used a processing Bragg grating that is identical to one used as a sensor. When the processing fiber grating was stretched periodically, the system of two gratings produced a carrier at this frequency with its phase modulated by the measured signal applied to the sensing grating.

Ezbiri *et al* [2010] published that in-fiber written Bragg gratings (FBGs) have been shown to offer many advantages over conventional interferometric and polar metric sensors in particular for applications requiring embedded sensors. In certain implementations, robust readout systems were necessary requiring immunity to vibration and the ability to operate at changing temperatures and pressure levels.

Ferreira *et al* [2010] gave a demodulation scheme for Fiber Bragg Grating (FBG) sensors. It was based on the generation of an electrical carrier by using a modulated multimode laser diode to illuminate the fiber grating. The change in Bragg wavelength was measured by tracking the phase of the carrier at the detector output in either an open or a closed-loop scheme. A theoretical analysis of the interrogation technique in terms of linearity and dynamic range was presented. Experimental data were obtained for both strain and temperature measurements. Sensitivities of 0.7 $\mu\varepsilon/\sqrt{Hz}$ and 0.05°C/$\sqrt{Hz}$ were obtained over a dynamic range of 60 dB. The application of this demodulation scheme to a multiplexed sensing system was also demonstrated.

Gang *et al* [2010] demonstrated the higher temperature sensitivity of a Fiber Bragg Grating (FBG) sensor when it is clad with a metal of a large thermal expansion coefficient. With lead (solder) cladding, the sensitivity of Bragg wavelength shift could be enhanced by about five (four) times. A theoretical model was adopted to show quite consistent results. It was found that thermal annealing was crucial for preparing high-quality Fiber Bragg Grating sensors with metal claddings.

Sung et al [51] experimentally demonstrated a new approach for the demodulation of a Fiber Bragg Grating (FBG) strain sensor by combining a tilted FBG demodulator with a temperature-independent property and a dual head FBG sensor with a temperature-discriminating property. This technique guaranteed a stable measurement independent of temperature perturbation at both sides of sensor and demodulator without any additional temperature-isolation or temperature-referencing process and had the minimum resolvable strain of 10 μ strain. The ranges of operating temperature at the sensor and at the demodulator which guaranteed a dynamic range of 1800 μ strain corresponding to the wavelength difference 2.2 nm between two notches of the tilted FBG spectrum were from room temperature to 180°C and 140°C, respectively.

Cavaleiro et al [2010] gave a description of hybrid fiber optic current sensor combining a metal-coated Fiber Bragg Grating with a standard current transformer. Measurements of the RMS current of power lines at 50 Hz with a resolution of 2 mA were demonstrated.

Chan et al [2010] showed that the wavelength detection accuracy of Fiber Bragg Grating (FBG) sensors was limited by various types of optical noises. For systems which used broadband sources, the received signal power was usually low, resulting in a low signal-to-noise ratio, especially when time-division multiplexing was used to multiplex a large number of sensors. In sensor systems using laser sources, although the signal power was relatively much higher, residual reflections in the system caused interferometric noise, which would limit the wavelength detection resolution.

Sung et al [2010] experimentally demonstrated a tilted Fiber Bragg Grating (FBG) demodulator that had a simple and compact scheme. Using this, wavelength-encoded information from a dual head strain sensor was demodulated with high stability and accuracy, independent of temperature perturbation at both sensor and demodulator FBG.

Jaehoon et al [2010] enhanced the temperature sensitivity of a Fiber Bragg Grating sensor by attaching two metals with different expansion coefficients to it. The temperature sensitivity could be changed by varying the metal lengths. The proposed temperature sensor could be applicable as a high sensitivity temperature sensor.

Spammer *et al* [2011] evaluated and use of fiber sensors in civil structures. Fiber Bragg Grating sensors have proved to be very well suited for applications such as structural health and performance monitoring. This paper reported on the use of Bragg gratings for strain measurements in concrete embedded civil structures. Sensors, attached to steel rebar, were characterized and subsequently embedded into the concrete deck of a steel truss bridge.

Sung *et al* [2011] introduced a Mach-Zehnder interferometer whose optical path difference was controlled by a tunable optical delay line. Using the interferometer as a demodulator for Fiber Bragg Grating sensors, intensity-based measurement of dynamic strain with a wide range of 0~1880 μstrain and 0~1 kHz was experimentally demonstrated.

Shenping *et al* [2011] presented a highly sensitive fiber temperature sensor based on a gain-switched Fabry–Perot semiconductor laser self-seeded from a linearly chirped Fiber Bragg Grating. A temperature resolution of better than 0.1°C was demonstrated. This sensor not only has the advantage of robustness against fluctuating light levels, but also obviates the need for fine wavelength discrimination.

Rochford *et al* [2011] showed that the peak reflectance wavelengths of gratings with reflectance maxima separated by less than 2 nm can be accurately determined through a demultiplexing method based on Hilbert transforms of interferograms. It was demonstrated that a wavelength de multiplexing of three Fiber Bragg Gratings (FBG's) with less than 4 pm crosstalk and repeatability and less than 19 pm uncertainty was possible. It was anticipated that a large number of gratings could be demultiplexed with a single broadband source and a single receiving interferometer, provided that the interferogram is sampled at accurate intervals slightly above the Nyquist rate.

Wei *et al* [2011] proposed a novel and short (5 mm long) fiber grating based sensor with a fiber grating Fabry-Perot cavity (GFPC) structure was fabricated and tested for simultaneous measurement of strain and temperature. The sensor exhibited unique properties that it possessed two spectral peaks within its main reflection band and the normalized peak power difference, in addition to its peak wavelength shift, it changed linearly with strain or temperature. The accuracy of this particular sensor in measuring strain and temperature was estimated to be ±30 μs in a range from 0 to 3000 μs and ±0.4°C from 20°C to 60°C, respectively.

Moreira *et al* [2011] gave a signal processing scheme for Fiber Bragg Grating sensors based on the utilization of adjacent modes of a multimode laser diode light source which allowed high sensitivity to be obtained over a large measurement range. For strain measurements, a range of 4800 μ; was achieved with a resolution of 0.08 μ;/Hz, yielding a dynamic range of 95 dB.

Chan *et al* [2011] reported on the use of a frequency-domain reflectometry technique for multiplexing Fiber Bragg Grating (FBG) sensors. This technique was based on the modulation of light intensity from a broadband source by a swept-frequency RF carrier. Signals from the FBG sensors located at different positions in an array were separated in the frequency-domain and demodulated using a tunable optical filter. A three FBG sensor system was experimentally demonstrated. The potential of the technique for multiplexing a large number of FBG sensors was also discussed.

Youlong *et al* [2011] presented a novel Fiber Bragg Grating displacement sensor. Using a uniform density and thickness overlapped dual-isosceles triangular cantilever beam as a strain agent, it was demonstrated both experimentally and theoretically that this sensor is able to automatically compensate for wavelength shifts induced by temperature. The measured sensitivity of this sensor was 0.1051 nm/mm within the working range of -18-18 mm.

Koo *et al* [2011] were instrumental in the dense wavelength division multiplexing of Fiber Bragg Grating sensors by combining code division and wavelength division multiplexing schemes. This approach allowed close spectral spacing among Bragg grating sensors without sensor spectral dynamic range limitation.

Koo *et al* [2012] also demonstrated dense-wavelength-division multiplexing (DWDM) of Fiber Bragg Grating sensors without sensor spectral dynamic range limitation by combining code-division and wavelength-division multiplexing schemes.

Sung *et al* [2012] introduced a novel scheme to obtain the I/Q signals optically using a dual head Fiber Bragg Grating (FBG) sensor and an optical-path-controlled Mach-Zehnder interferometer. Using this scheme as a demodulator for the FBG sensor, intensity-based measurement of dynamic strain was experimentally demonstrated.

Chi *et al* [2012] carried out an investigation of the performance of a time-division-multiplexed (TDM) Fiber Bragg Grating (FBG) sensor array using a tunable laser source. The system performance was found limited by the extinction ratio of the optical pulse modulator used for pulse amplitude modulation. Formulas that relate the crosstalk to the extinction ratio of the optical pulse modulator, the modulation parameters of the tunable laser, and the optical path differences among sensing channels were derived.

Chan *et al* [2012] also reported on the use of frequency-modulated continuous wave (FMCW) techniques for multiplexing Fiber Bragg Grating (FBG) sensors. This technique was based on the modulation of light intensity from a broadband source by a linear swept-frequency RF carrier. Signals from the FBG sensors located at different positions in an array were separated in frequency domain and demodulated using a tunable optical filter. The potential and limitation of the technique were discussed. A three-sensor FMCW multiplexed FBG array of parallel topology and a six-sensor hybrid FMCW/WDM system were experimentally demonstrated with -30 dB crosstalk between sensors and 2 μ resolution in terms of root mean square (RMS) strain value.

Jaehoon *et al* [2012] in their paper employed a novel demodulation scheme to monitor the dynamic perturbation of a Fiber Bragg Grating (FBG) sensor using an long-period grating (LPG) pair with erbium-doped fiber (EDF) inserted between the two LPGs. The experimental results showed that the proposed technique features high resolution and much more immunity to temperature perturbation compared to the conventional unbalanced Mach-Zehnder interferometer (MZI).

Sennhauser *et al* [2012] modeled mechanical and optical reliability of fibers and Bragg gratings at elevated temperature of up to 250°C and determined parameters in an extended test program. Stress corrosion and grating decay were investigated for two commercially available Bragg grating types.

Jaejoong *et al* [2012] introduced a Fiber Bragg Grating (FBG) laser sensor using a semiconductor optical amplifier (SOA) as gain medium. Experimental results showed good performance of the proposed laser sensor for multi-point sensing.

Seungwoo *et al* [2012] proposed a novel Fiber Bragg Grating (FBG) sensor demodulator using fiber birefringence. The demodulator was composed of a polarizing beam splitter (PBS), a polarization controller (PC), and a chirped fiber grating (CFG). In the sensor application of this paper, the CFG was used as a broadband reflection mirror. The experimental results showed that the demodulator had good performance for measuring static and dynamic strain.

Youlong *et al* [2012] gave a wavelength-division-multiplexing technique for interrogating 10-cascaded Fiber Bragg Grating sensing elements based on a ring-compounded-cavity fiber laser. A feedback control technique was introduced to a tunable Fabry-Perot filter that tracked the wavelength-shift of the sensor. The sensors were demodulated using an unbalanced scanning Michelson interferometer and a sensitivity of 1.682°/με was demonstrated.

Sungchul *et al* [2012] described a Fiber Bragg Grating (FBG) sensor demodulator using a chirped fiber grating. The demodulator used UV-induced birefringence of chirped fiber grating to interrogate the wavelength shift of a sensor FBG. The demodulator was composed of a polarizing beam splitter, a polarization controller, a single-mode fiber, and a chirped fiber grating. The proposed demodulator was immune to light power fluctuation and was cost-effective.

Seunghwan *et al* [2012] proposed and experimentally demonstrated a simple, passive, and self-referencing wavelength shift detection scheme for use in Fiber Bragg Grating sensing systems. The demodulation system was based on the interference between two modes in a polarization maintaining fiber loop mirror. Although it involved the use of an interference technique, it was stable as compared with other conventional interference demodulators.

Ying *et al* [2012] demonstrated a novel high-sensitivity pressure sensor, which was based on the use of a Fiber Bragg Grating (FBG) embedded in a polymer-filled metal cylinder with an opening on one side to enhance the pressure sensitivity. The measured pressure sensitivity of the fractional change in the Bragg wavelength of the experimental sensor was -3.41×10-3 MPa-1 which is approximately 1720 times higher than that can be achieved with a bare FBG. The linearity of the sensor was also good. This sensor could find applications in the area of low-pressure measurement.

Wait *et al* [2012] reported on a Brillouin optical time domain reflectometer-based distributed temperature sensor utilizing a Fiber Bragg Grating notch filter to suppress the Rayleigh backscatter in order to separate the Brillouin signal. The Brillouin light path was thus subject to minimum attenuation and was frequency independent. A 2-m spatial resolution was achieved over a range of 25 km with the temperature resolution rising from 1°C at the near end to 7°C at the far end in a measurement time of 10 min. This was reduced to <1°C over ~20 km if the measurement time was increased to 180 min.

Boulet *et al* [2012] described a novel technique to provide demultiplexing of Fiber Bragg Grating sensors, interrogated using interferometric wavelength shift detection. Amplitude modulation of multiple radio frequency driving signals allowed an acousto-optic tunable filter to provide wavelength demultiplexing. A noise limited strain resolution of 150 nanostrain/√(Hz) and a crosstalk better than -50 dB has been demonstrated.

Chan *et al* [2012] gave the use of gas absorption lines as multi-wavelength references to enhance the measurement accuracy of Fiber Bragg Grating sensors. Experiments with a three-FBG-sensor array interrogated by a tunable laser demonstrated an overall measurement accuracy of ~2 pm.

Cooper *et al* [2012] found that the sensitivity of measuring time multiplexed Fiber Bragg Grating (FBG) sensors could be improved by amplifying the signal returning from the sensors. This could be used to either improve the system performance or reduce the power, and hence the cost of the optical source. In the experiments, the addition of the amplifier allowed a reduction of >120 times in the source power.

Da Silva et al [2012] carried out strain studies in samples of power transmission cables by means of multiplexed optical Fiber Bragg Gratings. Calibration processes were presented. Strain was analyzed in individual wire conductors of the cable.

Barbosa et al [2012] initially inscribed a uniform Fiber Bragg Grating in a multimode fiber. It was observed that the phase matching condition was approximately satisfied by a few modes, causing the appearance of lateral lobes. Then they experimentally analyzed the dependence of these lobes upon variations in temperature. This study may lead to the construction of multimode temperature sensors.

Seunghwan et al [2012] discussed a simple, passive, and self-referencing wavelength shift detection scheme, for use with Fiber Bragg Grating sensing systems. The system was based on the use of a polarization maintaining fiber loop mirror.

Wade et al [2013] presented a fiber optic sensor device was developed incorporating a short length of erbium doped fiber fused in close proximity to a single-Fiber Bragg Grating, to measure both the fluorescent lifetime decay and the wavelength shift in these respective elements, for temperature and strain determination. Calibration results obtained from this simple, low cost, intrinsic sensor scheme showed standard deviation errors of 20.4 μ and 1.2°C over strain and temperature ranges of 22–1860 μ and 25–120°C, respectively.

Arregui et al [2013] presented a novel sensor capable of simultaneously measuring temperature and humidity fabricated and demonstrated using optical fiber waveguides. The sensor head was composed of a Fiber Bragg Grating and a low-finesse Fabry-Perot interferometric cavity. The Fabry-Perot cavity was fabricated using the electrostatic self-assembled monolayer process for the molecular-level deposition of materials of different thicknesses that form a humidity-sensitive coating on the end of the fiber, while the in-line Bragg grating fiber element was used to monitor temperature. Experimental results for a humidity range from 11% to 97% RH and for a temperature range from 10°C to 85°C were shown.

Gong et al [2013] reported a minimum variance shift technique for wavelength detection in Fiber Bragg Grating (FBG) sensors. The technique was demonstrated to offer high detection accuracy even when the spectrum of the FBG was in partial overlap with a neighboring FBG within a wavelength division multiplexed sensor array.

Frazao *et al* [2013] came up with a new scheme for simultaneous measurement of strain and temperature using a sampled Fiber Bragg Grating based on a long period structure written using the electric arc technique. The temperature and strain measurement resolutions were estimated to be ±0.50°C/√Hz and ±3.38 με/√Hz, respectively.

Murphy *et al* [2013] demonstrated a spatially-scanned interferometric technique for demodulation of Bragg grating sensors, overcoming the 'moving parts' and measurement bandwidth limitations associated with temporally scanned interferometric schemes. The wavelength measurement was derived from the phase of the complex analytic signal of spatial inter ferogram, in contrast to spectral measurement by FTS. The technique incorporated precise delay mapping based on the analytic signal of a laser inters ferogram, thus overcoming limitations of conventional spatial interferometers caused by no uniformities in optical surfaces and in the imaging array. Murphy *et al* achieved a resolution of 25 pm for a limited OPD scan of 200 mm. This result compared favorably to reported temporally-scanned schemes and indicated potential for far higher resolutions and measurement bandwidth in larger spatial interferometer designs using long high-speed imaging arrays.

Teunissen *et al* [2013] highlighted that based on the changes occurring in the electricity market, online monitoring of h-v transformers becomes an important aspect to supervise the actually operating conditions of old devices and to assess the residual lifetime. The use of optical sensors based on Fiber Bragg Gratings offers the possibility to measure the temperature and the partial discharges directly at the active part of h-v transformers. For a successful integration of the FBGs inside the transformer the long-term stability and optical fiber's influence on the dielectric strength of transformer oil was investigated.

Fernandez *et al* [2013] presented that Fiber Bragg Grating sensors were being evaluated by the nuclear industry for structural integrity and temperature monitoring. Radiation effects on FBG sensors have been reviewed and in-reactor core irradiation of FBG temperature sensors has been discussed.

Betz, *et al* [2013] published that the field test has shown the great potential of fiber-optic Bragg gating sensors. They were suitable for load monitoring of aviation structures under real-world conditions. The results obtained with the Bragg gratings showed excellent consistency with the strain gage results. This indicated that both the sensor installation technique of gluing the sensors to the surface and the sensor interrogation technique using a tunable laser-based system, both of which were studied in the field test, were well-suited for these measurements.

Hua *et al* [2013] have successfully demonstrated the application of Fiber Bragg Grating sensors to detect the solder interconnect de-bounding between flip chip ball grid array and printed circuit board in four-point bend tests. Four sensors, due to their small size, were surface-mounted on the four-corners of the ball grid array substrate, about 1 mm from the solder balls that allow more sensitive strain measurement under board flexure. The measured strain data was compared with the data from strain gauge, daisy chain resistance, and dye and pry test. The preliminary results showed that the fiber sensors were capable of detecting the onset of solder joint fracture, strain relaxation, and extent of the failure.

Ping *et al* [2013] gave a new fiber-optic sensor for simultaneous measurement of water-soluble analyses and temperature with polymer-coated Fiber Bragg Gratings (FBGs). As an application of the approach, simultaneous monitoring of the concentration of sugar or potassium chloride (KCl) and temperature was achieved. Changes in these environmental parameters resulted in different extents of either red- or blue-shifts of the Bragg resonance wavelengths of the gratings.

Peng *et al* [2013] proposed a Fiber Bragg Grating (FBG) sensor system with a two-level ring architecture. The survivability and capacity of a FBG for a multipoint sensor system were enhanced by adding remote nodes and optical switches in the two-level ring architecture. Additionally, to enhance the signal-to-noise ratio (SNR) of the sensor system, a fiber ring laser approach was utilized to construct the proposed two-level ring architecture. The fiber ring laser adopted herein yielded the high SNR of the sensor system. The proposed system could increase the reliability of FBG sensor systems for multipoint smart structures.

Song *et al* [2013] presented a novel pressure sensor structure comprising a carbon fiber ribbon-wound composite cylindrical shell. Based on this mechanical structure combined with a Fiber Bragg Grating (FBG), an accurate low-pressure sensor was developed. Theoretical analysis and first-principle investigations were conducted. Further, experimental results indicated that the pressure sensitivity and measurement range could reach 0.452 nm/MPa and 8 MPa, respectively.

Yinping *et al* [2013] described a relative humidity (RH) sensor based on tilted Fiber Bragg Grating (TFBG) by utilizing polyvinyl alcohol (PVA) as the sensitive cladding film. RH increasing in the PVA coating would result in reduction of refractive index. Due to the TFBG's sensitivity to ambient refractive index, the spectral properties of PVA-coated TFBG were modified under exposure to different ambient humidity levels ranging from 20% to 98% RH. The transmission power of TFBG had different linear behaviors for two different humidity ranges (20%-74% RH and 74%-98% RH), and the sensitivity for each humidity range reached as high as 2.52 and 14.947 dBm/%RH, respectively.

Muller *et al* [2013] presented that an embedded Fiber Bragg Grating could be subjected to arbitrary states of strain including shear strain. Such perturbations could cause coupling between polarization modes. Coupled-mode theory in Bragg gratings so far neglected this effect and only considered forward-backward coupling. Polarization mode coupling within a Bragg grating lead to interdependencies between Bragg reflections peaks which had so far been unaddressed. A full strain tensor treatment of Fiber Bragg Gratings, considering the coupling of the polarization modes within the grating was formulated.

Seongmin *et al* [2013] presented a highly sensitive Fiber Bragg Grating temperature sensor using a temperature-sensitive Pb/Ge-codoped fiber experimentally with the average temperature sensitivity of the resonance wavelength shift about 0.0176 nm/degC.

Han *et al* [2013] gave a simple and practical scheme for a directional bending sensor based on a sampled chirped Fiber Bragg Grating. The proposed sensing method had temperature insensitivity. The wavelength spacing in the reflection spectrum of a sampled chirped Fiber Bragg Grating was changed by bending because of the modification of the chirp ratio. As positive or negative bending was applied to the sampled chirped Fiber Bragg Grating embedded on a flexible cantilever beam, the wavelength spacing increased or decreased because of the induction of the tension and the compression strain gradient along the fiber grating.

Ambrosino *et al* [2013] in their work showed the dependence of the magneto strictive response on the prestress used to improve and fit the performance of Terfenol-D based Fiber Bragg Grating magnetic sensor. The possibility to tune sensitivity allowed to work at different operative conditions and to develop advanced sensors with reconfigurable sensitivity. Performance improvements in terms of magnetic resolution up to 0.0116 A/m were demonstrated.

Grobnic *et al* [2013] presented a narrowband multiple high-order Bragg resonances from a single Bragg grating structure inscribed using a femtosecond IR laser and a 4.28 mum pitched phase mask were used to demonstrate a multi parameter sensor in standard low cutoff wavelength optical fiber. Six high reflectivity resonances that are observed in the wavelength range from 1 to 2 mum can be used to monitor up to six sensing parameters. Temperature and strain coefficients of the grating at each of the high-order Bragg resonances were evaluated.

Dong *et al* [2013] came up with a novel technique for chirp control of a uniform Fiber Bragg Grating (FBG) based on the special strain function modulation. A cylinder taper cantilever beam (CTCB) was specially designed and capable of providing special position-dependent strain function gradients along an originally uniform FBG, which allowed tunable quasi-triangular and quasi-Gauss-gradient FBG filter. Furthermore, the feasibility of the tunable chirped FBG based on the strain function modulation as sensor was validated. This state-of-art technique was expected to be applied in fiber filter, FBG sensor and multi wave length fiber laser.

Fu *et al* [2013] presented and demonstrated a novel Fiber Bragg Grating (FBG) sensor configuration using three broadband light sources of different wavelength bands for the interrogation of FBG sensors distributed over 75 km of fiber. Rayleigh backscattering was reduced and a 60-dB effective dynamic range was demonstrated.

Suleiman *et al* [2013] showed an innovative investigation of optical feedback or self-mixing interference within the cavity of a single-longitudinal-mode laser as an integral part of a novel interrogation scheme to be employed in a Fiber Bragg Grating-based sensor for strain measurement. The entire sensor device simply consisted of a laser diode with an integrated photodiode which was coupled to a Fiber Bragg Grating under strain. A small percentage of the injected light wave resonantly reflected off the grating structure reentered the laser cavity and modified the emission properties of the laser, resulting in the formation of characteristic saw tooth fringes which contained the embedded strain information.

Caucheteur *et al* [2013] presented the explosion risk linked to the use of hydrogen as fuel requiring low-cost and efficient sensors. A multipoint in-fiber sensor capable of hydrogen leak detection in air as low as 1% concentration with a response time smaller than a few seconds was presented. This solution made use of Fiber Bragg Gratings (FBGs) covered by a catalytic sensitive layer made of a ceramic doped with noble metal which, in turn, induced a temperature elevation around the FBGs in the presence of hydrogen in air.

Qizhen *et al* [2013] presented and demonstrated a novel time-division-multiplexing Fiber Bragg Grating (FBG) sensor for multipoint temperature warning sensor. A multi wave length pulsed laser based on a multichannel matched FBG was employed. The sensor array consisted of multiple uniform FBGs at different positions and with different nominal wavelengths. When the temperature exceeded the threshold at a certain position, the light at the corresponding time slot and wavelength could be detected. The sensor provided a simple and flexible solution to locate the abnormal temperature increase with different tolerable thresholds at different locations.

Yong *et al* [2013] described a double-arched-beam-based Fiber Bragg Grating (FBG) sensor for displacement measurement. Unlike most FBG sensors that measured the resonance wavelength shifts to detect the measured, this kind of FBG sensor was proposed to measure the displacement based on the demodulation of the FBG's reflective spectra bandwidth. According to the strain distribution on the novel double-arched beam surface, the positive and negative strain would act on only one FBG, which was stuck on the beam surface. Thus, the positive and negative strain would make the spectra broaden as the displacement increases.

Wei *et al* [2014] gave a simple anisotropic structure made by carbon fiber laminated composite for fabricating a high pressure sensor. A pressure sensor with good sensitivity over a broad measurement range was fabricated by using Fiber Bragg Grating and the anisotropic carbon fiber laminated composite structure. The characteristic responses of pressure and temperature of the new pressure sensor were analyzed. Experimental data showed that when the pressure changes from 0 to 70 MPa, the wavelength shift of the Fiber Bragg Grating pressure sensor was up to 7 nm, corresponding to a sensitivity of 10 kPa/pm.

Fu *et al* [2014] presented a novel high-speed Fiber Bragg Grating (FBG) sensor interrogator using dispersion-compensating fiber. The wavelength shift measurement of the FBG sensor was converted to time-domain measurement. The high-speed potential of this scheme was investigated experimentally, demonstrating an effective sampling speed of 2.44 mega samples per second.

Tosi *et al* [2014] innovated a novel interrogation technique for Fiber Bragg Gratings, based on the self-mixing effect in strong feedback regime and intensity detection, through experimental measurements. The application of an appropriate spectral estimator permitted transferring the analysis into the frequency domain, leading to the realization of a power drift-tolerant strain sensor.

Yong *et al* [2014] described the dynamic testing and control results obtained with an exoskeleton robot finger with embedded fiber optical sensors. The finger was inspired by the designs of arthropod limbs, with integral strain sensilla concentrated near the joints. The use of Fiber Bragg Gratings (FBGs) allowed for embedded sensors with high strain sensitivity and immunity to electromagnetic interference. The embedded sensors were useful for contact detection and for control of forces during fine manipulation. The application to force control required precise and high-bandwidth measurement of contact forces.

Wei *et al* [2014] improved the performance of FBG sensors in a wavelength-division multiplexed sensor network using genetic algorithm. Simulation and experiment showed that computed speed and capability of multiplexing are enhanced, and the measurement range of sensors in FBG sensor network is increased while using improved genetic algorithms with proper parameters.

Haibin *et al* [2014] demonstrated a novel wireless sensors network available for multi-dimension and multi-parameter measurement based on Fiber Bragg Grating sensing units. The combination of wireless communication with the Fiber Bragg Grating sensors obtained obvious advantages including inherent immunity to electromagnetic interference, compact size and high sensitivity compared with conditional wireless sensing network based on electronic elements.

Myonghwan *et al* [2014] gave precise information on spatial distributions of temperature important for diagnosing power transformers and evaluating its life because a power system failure results in an enormous loss in tangible as well as social. The optical Fiber Bragg Grating (FBG) sensors, which have been studied intensively for last decade, could be very efficient tools for applications to above mentioned purpose because these are immune to EMI and can be highly multiplexed, which enables efficient quasi-distributed temperature sensing along tens of km range.

Kunzler *et al* [2014] showed that optical Fiber Bragg Grating sensors exhibit specialized sensing characteristics for harsh environments. The most common interrogation methods for FBGs require high resolution spectrometers that are not well suited to some embedded test situations.

Hwa *et al* [2014] highlighted that railway is an important part of the transportation systems in many parts of the world. Results obtained from a FBG sensor network installed on 26-km rail track and several train-borne monitoring systems demonstrated that FBG has the potential to revolutionize the railway industry.

Wild *et al* [2014] presented an intensiometric detection system for Fiber Bragg Grating sensors. The system is designed to directly detect intensity modulated signals, or to convert spectrally modulated signals into intensity modulated signals.

Foo *et al* [2014] presented a novel non-intrusive respiratory monitoring system for detection of life threatening situations in bedridden or bed bound patients, and for monitoring of sleep disorders in elderly or patients. Specifically, the subtle design and implementation of a system using Fiber Bragg Grating pressure sensors to monitor the respiratory rate without requiring the patients or elderly to wear any probes has been presented.

Canning *et al* [2014] regenerated gratings seeded by type I gratings to withstand temperatures beyond 1000degC. A new approach to increasing temperature resistance of ultra high T stable gratings was presented.

Franke *et al* [2014] gave more advanced robotic applications requiring high accuracy positioning of the robot manipulator. They introduced a novel approach to measure the elastic deformations of robot links in order to improve its pose accuracy using Fiber Bragg Gratings.

Xinlong *et al* [2014] undertook first step experimental researches about embedded Fiber Bragg Grating (FBG) sensors network for health monitor of solid rocket motors (SRM. In the experiment, the FBG sensors networks were embedded in composites plane with simulative de-lamination and scale SRM models. The results of the plane bend test indicated that

damage could be identified by detecting concentration strain field, and the results of the scale SRM shells internal hydraulic pressure test indicated that the complex strain and deformation could be monitored by the sensors network, leading to the possibility to develop FBG sensors network systems for composites SRM health monitor.
Ke *et al* [2014] presented a temperature sensor based on fibers Bragg grating in photonic crystal fibers. The temperature property of uniform fibers Bragg grating in photonic crystal fibers was studied. By finite element method, the relation between the birefringence in photonic crystal fibers and the temperature was analyzed.
Yanliang *et al* [2014] analyzed the strain-temperature cross sensitive characteristic of optical Fiber Bragg Grating (FBG) theoretically, designed and made a novel FBG strain sensor. It had a temperature-compensated function, and it improved the effect of being sensitive to strain. To a certain extent, this sensor overcame the traditional temperature-compensated methods easy to have a creep and aged phenomenon.
Espejo *et al* [2014] gave a new method for measuring transverse stress with 10.2-mum spatial resolution in a Fiber Bragg Grating sensor, without the use of polarization-maintaining fiber, by combining a four-state polarization analysis with a layer-peeling algorithm. Measurements of the externally induced birefringence agreed well with predicted values. It was also demonstrated that the measurement is insensitive to temperature changes and spatial gradients, making it ideal for no isothermal applications.
Saini *et al* [2014] demonstrated that the etched-core Fiber Bragg Grating sensor could be used to detect down to a monolayer of biological and chemical agents immobilized on the surface of the fiber. Theoretical models based on calculating the effective index of the surrounding medium in the presence of immobilized layers were developed and confirmed experimentally by immobilizing a monolayer of 3-aminopropyl-monoethoxydimethyl-silane (APMDS) and polymers of 3-aminopropyl-triethoxysilane (APTES) on the surface of the fiber.
Shengchun *et al* [2014] presented a time-division multiplexed Fiber Bragg Grating (FBG) sensor system capable of real-time monitoring. It was based on an unbalanced Michelson interferometer, a delay signal generator, and a tree-structured single-pole-double-throw switch array. Realization of real-time monitoring was because the arriving time of sensing signals was synchronized with the controlling signals of the switches.
Saitoh *et al* [2014] presented a long-distance Fiber Bragg Grating (FBG) sensor system developed using a wavelength-swept light source with output power turned on-off and timing synchronized to the sweep signal to reduce optical noise caused by Rayleigh scattering generated from the transmission fiber. This system could detect changes in the FBG reflection wavelengths even if the FBG is 120 km from the sensing position.
Binfeng *et al* [2014] presented a highly sensitive liquid-level sensor based on etched Fiber Bragg Grating (FBG). The transmission dips of FBG spectra were affected by the fraction of the length of the etched FBG that was surrounded by the liquid. The experiments showed that for a liquid-level variation of 24 mm, the transmission dip difference changed about 32 dB.
Ambrosino *et al* [2014] demonstrated a magnetic field sensor based on the integration of a Fiber Bragg Grating (FBG) with a magnetic shape memory alloy (MSMA). MSMA is a new kind of material able to show extremely large strains in response to a magnetic field. Moreover, differently from classical shape memory alloys, which were actuated by temperature, MSMAs normally show quite fast responses.
Michael *et al* [2014] found the use of liquid hydrogen as a fuel requires low-cost multipoint sensing of hydrogen gas for leak detection and location well below the 4% explosion limit of hydrogen and presented a multipoint in-fiber hydrogen sensor capable of hydrogen detection below 0.5% concentration with a response time of less than 10s.
Huang *et al* [2014] presented a demodulation algorithm for Fiber Bragg Grating (FBG) sensor. The proposed demodulation algorithm evaluated the wavelength shift in the reflected spectrum of an FBG sensor. It computed the cross-correlation between the perturbed spectrum and the undisturbed spectrum.
Guo *et al* [2014] gave a technique for temperature-immune pressure measurement using a strain-induced quadratic-chirped Fiber Bragg Grating by differential optical power detection. Linear pressure measurement up to 20 kPa with a resolution of 0.05 kPa and thermal stability less than 2% full-scale for a temperature range from 0 to 80degC were achieved using pin photodiodes detection, without any temperature compensation.
Thus the ability to inscribe intra-core Fiber Bragg Gratings (FBGs) in germanosilicate core photosensitive fibers in the recent years has revolutionized the fields of telecommunication and optical fiber sensor technology. Fiber Bragg Gratings are realized by permanently changing the index of refraction in a periodic pattern along the core of the fiber by exposing them to intense UV radiation. This periodic modulation of the index of refraction in the fiber core acts like a selective mirror for the Bragg wavelength of the structure. As the spectral properties of FBGs are highly dependent on the grating period, the FBG properties are very sensitive to changes in the length of the fiber into which they are inscribed. This

property makes FBGs excellent all optical sensors for smart structures, process control, geophysical research and mining applications.

7. Applications

Bragg Gratings have proven attractive in a wide variety of optical fiber applications, such as
Narrowband and broadband tunable filters

- Optical fiber mode converters
- Wavelength selective filters, multiplexers, and add/drop Mach-Zehnders
- Dispersion compensation in long-distance telecommunication networks
- Gain equalization and improved pump efficiency in erbium-doped fiber amplifiers
- Spectrum analyzers
- Specialized narrowband lasers
- Optical strain gauges in bridges, building structures, elevators, reactors, composites, mines and smart structures

It is evident that the demand for more bandwidth in telecommunication networks has rapidly increased the development of new optical components and devices. Current efforts of research and development are aiming at increasing the total capacity of optical fibers as a medium and improving long haul optical transmission systems using new innovative technologies such as ultra-dense wavelength division multiplexing (WDM). The advances in the optical communications have been synergized by development of efficient and powerful optical components which eliminate the need of costly conversions from optical to electrical signal and back . Fiber Bragg Gratings have been vital in the phenomenal growth of some of these products and are recognized as one of the most significant enabling technologies for fiber optic communications.

8. References

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