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A comparative study of Fiber Bragg Grating based tilt sensors

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ABSTRACT

Tilt-angle monitoring is of extreme importance for the health monitoring of various civil infrastructures such as tunnel, bridges, dams, etc. In addition, it is also one of the key parameters to be monitored in mechanical, instrumentation, robotics, aeronautical engineering applications. Hence, a very accurate, sensitive and compact tilt-monitoring sensor-system capable of resolving lowest possible tilt with a large dynamic range would be of extreme importance. In contrary to electronic tilt sensors, the most striking feature of all optical sensors is its immunity towards electromagnetic interference, which makes them deployable in harsh and high-EMI environments. Significant progress has already been made on all-optical sensing with the manufacturing of in-fiber Bragg grating (FBG), which immediately has become useful in numerous applications over other types of optical fiber sensors and has open up a new domain of research. In most of the proposed techniques a solid mass is used with several optical fibers, with in-built Bragg gratings, connected in orthogonal directions. To make the tilt sensor insensitive to temperature variation, several FBGs are installed within the system and only the difference in response between the FBGs are considered for calculation of tilt. This nullifies the effect of temperature on the FBG. There are also FBG based tilt sensors which are sensitive to temperature and therefore they can be used as temperature sensors as well. This paper aims to review the techniques of implementation of tilt sensors as published by the research community and to compare their relative performance.

Keywords: Fiber Bragg Grating, Tilt Sensor, Pendulum, Weight Mass

1. INTRODUCTION

Optical fiber sensing technology has obtained lots of attention and achievements in the last decade of rapid development. The ultimate target in development of optical fiber sensing technology is to display and exhibit its technical superiority, and therefore generate wide applications in industry. Because of its many advantages including its immunity towards electromagnetic interference, chemically inert even against corrosion, light weight, low-cost optical fiber sensors have found wide applications in many fields. In the category of fiber optic sensors, Fiber Bragg Gratings (FBGs) are desirable because of their high sensitivity, simple installation, large operational bandwidth and multiplexing capability [1-2]. Nowadays lots of FBG based sensor components have been developed and implemented including temperature sensors, gas sensors, stress/strain sensors, vibration sensors, and accelerometers and so on[3-8]. However there still exist gaps to meet customer demand such as highly sensitive tilt measurement.

Some key techniques for optical fiber sensing technology was thoroughly investigated according to engineering demands and to solve technical problems and therefore to be used more effectively. Other than temperature and strain measurements, great efforts have been made by the researchers to develop various kinds of FBG-based sensors to detect parameters such as pressure, acceleration, force, tilt etc. This paper reviews on several typical structures and application of Fiber Bragg Grating sensors for tilt measurement. It is expected to provide some useful hints for FBG based tilt sensors for wider industry applications.

2. FIBER BRAGG GRATING THEORY AND SENSING PRINCIPLE

A fiber Bragg grating is a type of distributed Bragg reflector constructed in a short segment of optical fiber. When broadband light is inserted into the fiber, the inscribed Bragg gratings act as mirrors that reflect particular wavelengths of light [9]. These reflected wavelengths can be valuable tools to measure several parameters such as strain, temperature, tilt, acceleration, and others. Basically, a Bragg grating is a longitudinal periodically modulated refractive index profile in the core of an optical fiber (see Fig. 1). They are produced by exposing the core of the optical fiber to an intense spatially-varying pattern of ultra violet light.

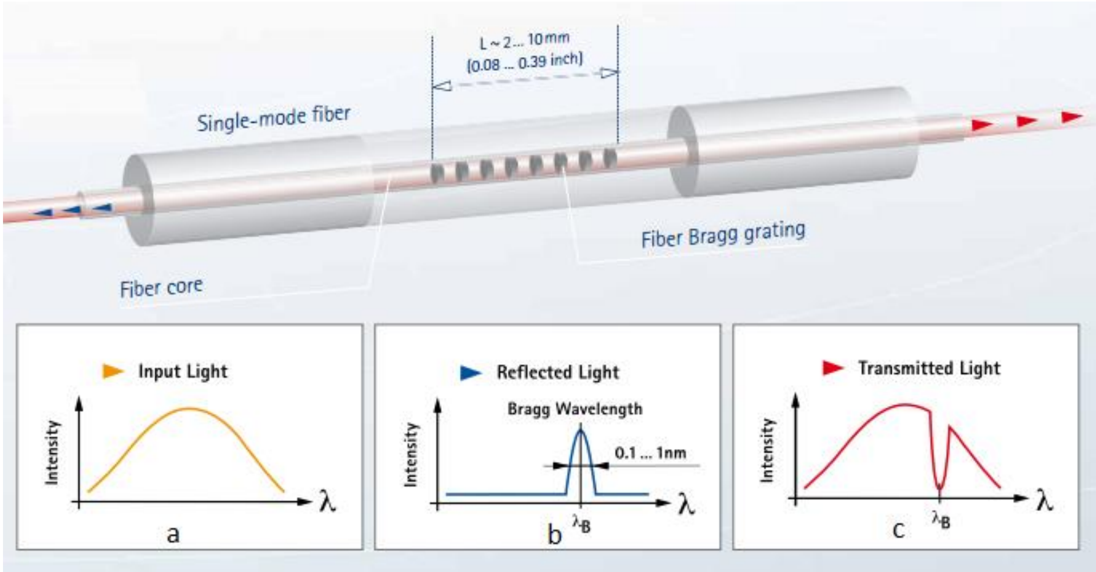

Figure 1. Structure of a Fiber Bragg Grating [9]. a. Intensity distribution for Incident Light, b. Intensity distribution for Reflected Light, c. Intensity distribution for Transmitted Light

When light travels through a fibre, it travels essentially in one dimension, and every time it meets a discontinuous change, a small amount of energy is reflected. In general, it is expected that these reflections are very small and indeed it is true for an arbitrary wavelength. These weak reflections have no particular phase relation with each other. Hence it is giving only a small total reflection for the grating as a whole. In order to have a strong overall reflection, it is important that the reflected wave interfere constructively. The Bragg condition for that is expressed as

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

where λ_B is the Bragg wavelength of FBG, n_{eff} is the effective refractive index of fiber core and Λ is the grating period. The wavelength which satisfies the Bragg condition is reflected back from the grating region and rest is transmitted. The reflectance of the input light achieves a peak at the Bragg wavelength. Equation (1) gives us the wavelength that will undergo a strong reflection.

In a FBG sensor, the measurand causes a shift in the Bragg wavelength, $\Delta\lambda_B$. The relative shift in the Bragg wavelength, due to an applied strain can be measured. Essentially, any external agent that is capable of changing Λ will displace the reflected spectrum centred at Bragg wavelength. A longitudinal deformation, due to an external force, for instance, may change both Λ and n_{eff}, the latter by the photo-elastic effect and the former by increasing the pitch of the grating.

3. REVIEW OF FBG BASED TILT SENSORS

A tilt sensor is an equipment that is used for measuring the tilt in multiple axes of a reference plane. Tilt sensors measure the tilting position with reference to gravity, and are used in numerous applications such as understanding of vertical and horizontal inclination of an airplane, health monitoring of high rise buildings or bridges, detect the position of hand-held game systems and in game controllers etc. FBG based tilt sensor generally use a structure where one or more fibers get strained because of the inclination of the structure [10-16]. Measurement of tilt in different directions is possible using multiple sensors. The key specifications of tilt sensors include number of measuring axes, resolution, sensitivity, measuring range etc.

Fiber Bragg grating has been used as tilt senor. Chen et al. [12] describes a tilt sensor, shown in Fig. 2, using a system where an iron ball is placed between two Fibers. In one Fiber, Bragg Grating is written and other one is the dummy fiber. The system is placed in an aluminium box. A polyvinyl chloride (PVC) cylinder is placed on one end of the aluminium box. One end of a fiber is anchored with PVC cylinder whereas other fiber is fixed with the inner surface of the aluminium box. If the system is tilted, the ball will move to one side because of gravitational force which will create strain on the FBG resulting a wavelength shift. The wavelength will depend on the nature of the strain i.e. compressive or elongated. The PVC cylinder in one end with proper length is used to compensate the strain due to temperature change. The accuracy of ±0.167° in tilt angle measurement and ±0.33° temperature stability over the temperature range 27 °C - 75 °C is reported.

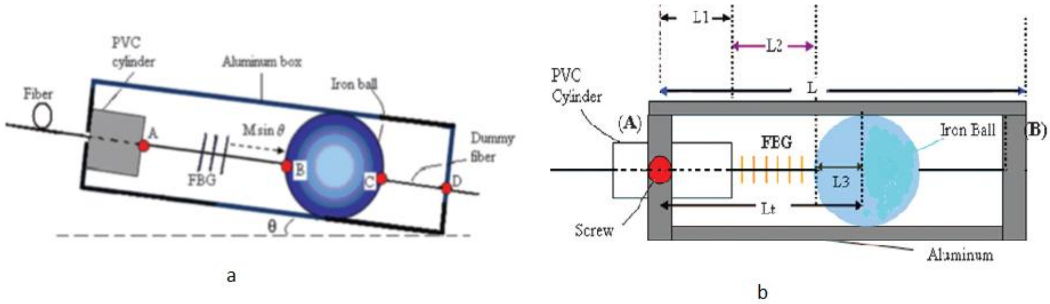

Figure 2. System proposed by Chen *et al.* [12] a. Tilt sensor with an FBG contained in an aluminium box, b Cross sectional view

Yang et al. [13] demonstrated a 2-D tilt angle measurement system using FBG. The system is shown in Fig. 3a and it can measure temperature along with tilt. The sensing system consists of two fiber Bragg gratings (FBGs) attached to a specially designed columnar pendulum. Two parts the pendulum rod consists of different materials having difference in CTE and Young's modulus. Two FBGs were used in this system one glued on its surface and another along the line of the two parts in the centre. One end of the pendulum is fixed on top frame where as a mass is attached on the other surface. For any applied inclination, two orthogonal tilt angles can be detected respectively by the wavelength shifts in two FBGs. A maximum tilt angle sensitivity of 0.074 nm/°, accuracy of 0.18°, and temperature sensitivity of 0.021 nm/°C have been achieved within the tilt angle range of 0°–40°.

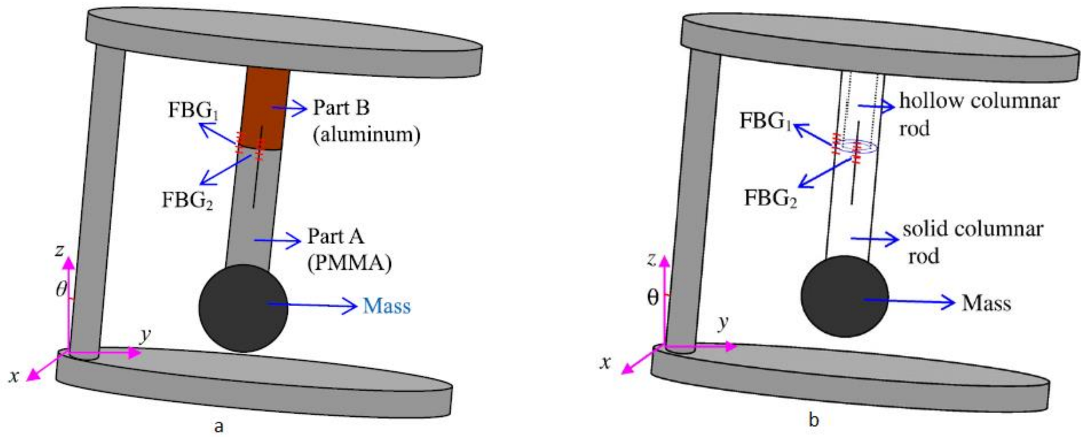

Figure 3. Schematic diagram of Tilt sensor proposed by a. Yang *et al.* [13], b. Bao *et al.* [14]

FBG-based 2-D tilt sensor was reported by Bao et. al. [14] using a specially-designed rod of hybrid columnar pendulum and two FBGs. As shown in Fig. 3b, upper half of the rod was hollow while other half was solid. Two FBGs are attached on the surface at a distance of one fourth of the circumference of the rod of pendulum and across the interface of its hollow and solid parts. Reflection peaks of FBGs split by the applied tilt angle. By measuring the shift in reflection peaks, 2-D tilt angle can be measured. The system is inherently insensitive to temperature. Tilt angle sensitivity is 0.054 nm/° has been reported for a tilt angle range of 20° with an accuracy of 0.27°.

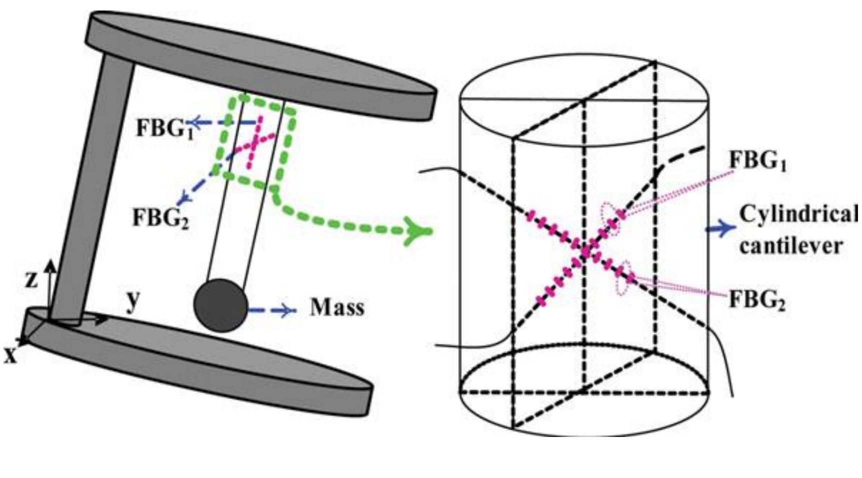

Figure 4. Design of the tilt sensor based on two FBGs proposed by Dong *et al.*[15]

A fiber optic tilt sensor has been experimentally demonstrated by dong et al. [15] based on two FBGs embedded in a cylindrical cantilever-based pendulum. By measuring the reflected optical power of the chirped FBGs, temperature-insensitive measurement of 2-d tilt angle has been realized. Two FBGs were embedded in a cylindrical cantilever based pendulum in two orthogonal planes. Tilt induced bending of the pendulum changes reflected optical powers and spectrum of the two FBGs. Sensitivity of 42.97 nw/° with measurement accuracy of 0.27° has been reported over a range up to ±15°.

In another work, dong et al. [16] have realized a tilt sensor exploiting the strain induced chirp characteristics of three FBGs. Both the sensors were based on vertical pendulum mechanism. A reasonably good resolution was achieved in the first case whereas a good accuracy was achieved in both the cases. However, as the angle transduction in both the sensors was realized by vertical pendulum structure, the performance of these designs are limited by the errors associated with mechanical joints and frictions of the pendulum suspension mechanism and the pre-deflections of steel flakes.

A temperature insensitive FBG based tilt sensor with large dynamic range has been reported by au et al. [17]. The schematic of the proposed sensor configuration is depicted in fig. 5. It comprises a square metallic frame, a thin cylindrical object mass and four FBGs. A single fiber is glued at the mid-point of each four arms of the square to realize a cross in the upper plane of the metallic frame. Four FBGs are inscribed over these fibers in such a way that they remain at the centre of the four arms of the cross. Each of the fibers is strained equally along the two directions when it is glued on the frame. FBGs, with reflection wavelengths defined as $\lambda_i, (i = 1,2,3,4)$ determine the strain of each fiber segment. The cylindrical object is fixed so that its centre of gravity coincides with intersection point of the virtually extrapolated fibers and hence at the centre of the square frame at the fiber optic plane. Upon inclination of the metal frame from the vertical axis of the sensor, strain induced in the four fiber segments of the cross will vary. Fig. 5 shows the case when the sensor is tilted to an angle θ in the *x-z* plane while keeping inclination in *y-z* plane zero. In addition, the proposed sensor configuration completely eliminates the cross-sensitivity arises from thermo-optic effects in FBG.

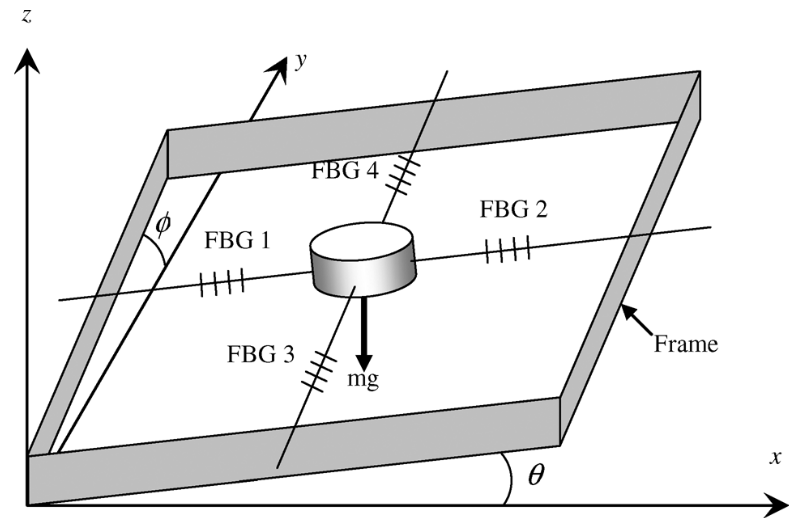

Figure 5. Schematic diagram of FBG based tilt sensor by Au *et al.* [17]

The modified sensor configuration as proposed by Au et al. [17] is depicted in Fig. 6. The cubical design of the sensor comprises the square bottom frame, a spherical proof mass (instead of the cylindrical proof mass), four FBGs and an additional roof top plate. The proof mass is hanged from the centre of the roof top plate in such a way to keep its centre of gravity (CG) in the horizontal plane passing through the top of the bottom frame. A single fiber, passing through the centre of the sphere, is glued inside the sphere as well as at the mid points of each section of the bottom frame to realize a perfect cross of equal arm lengths. The centre of the cross coincides with the CG of the proof mass which also keeps the four arms of the cross perfectly horizontal in this arrangement. Weight of the proof mass is totally supported by the vertical fiber when the sensor is placed on a horizontal surface and there would be no induced strain in the four segments of the horizontal fibers.

In Comparison of the sensor response of the modified design to the first design, the modified one shows a high degree of measurement accuracy, repeatability and sensitivity. The additional fiber in the modified design ensures the centre of the spherical mass aligned to the upper surface of the rectangular frame and the gravity induced angle effect is eliminated. This sensor is designed to measure magnitude as well as the direction of inclination from the horizontal to over ±30°. A sensitivity of 0.0395nm/°, resolution of 0.013° and accuracy of 0.051° were achieved.

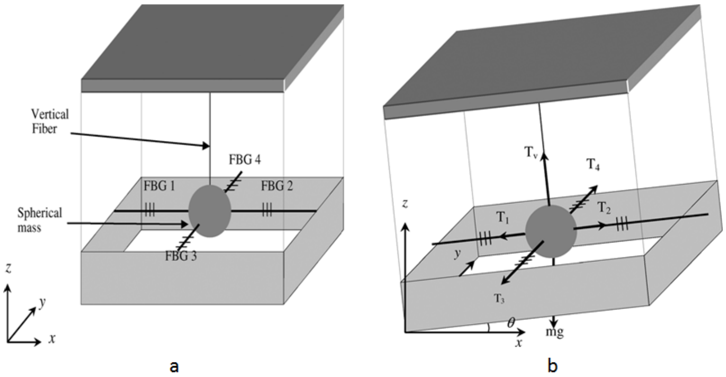

Figure 6. a. Modified schematic diagram of FBG based tilt sensor by Au *et al.* [17], b. Force diagram of modified tilt sensor with tilt angle θ in x-z plane and zero in y-z plane by Au *et al.* [17]

4. CONCLUSIONS

With the development of optical fibers, it was concluded that they could also be used as sensors. Optical fiber sensors have unique advantages such as high sensitivity, immunity to EMI, small size, lightweight, robustness, and the ability to provide multiplexed or distributed sensing. Although the optical fiber sensors have not experienced the dramatic commercial success of optical fiber communications, they have been continuously and enthusiastically studied. Fiber grating sensors have been the most widely studied topic among various optical fiber sensor technologies. Some fiber grating sensors have been commercialized for civil health monitoring and oil industries. In this paper, an introduction to the optical fiber sensors has been discussed and the current status of FBG based sensors has been briefly reviewed. Most of the techniques use solid mass either hanged through cross directional fibers or planted inside cylinder. But whatsoever be the implantation method, it ultimately uses the change in stress in the fibers due to gravitational force on the object mass of the inclined sensor.

Table 1. A comparative result of different FBG based tilt sensors

Method	**Angle of inclination**	**Sensitivity**	**Resolution**	**Accuracy**	**Temperature Sensitivity**
Chen *et al.* [12]	±10°	0.06nm/°	0.0067°	0.167°	0.0004nm/°C
Yang *et al.* [13]	0°-40°	0.074nm/°	0.12°	0.18°	0.021nm/°C
Bao *et al.* [14]	0°-20°	0.054nm/°	0.19°	0.27°	NA
Dong *et al.* [15]	±15°	42.97nW/°	0.01°	0.27°	NA
Au *et al.* [17]	±30°	0.0395nm/°	0.013°	0.051°	NA

Table 1 shows the comparative result of different methods as published by the researchers. Commonly used parameters for measuring the performance of the sensor are: (i) range of inclination angle over which the sensor works satisfactorily, (ii) sensitivity of the sensor indicating the change in wavelength per degree change in inclination angle, (iii) resolution of the sensor indicting minimum change in inclination angle that can be sensed by the sensor and (iv) accuracy indicating shift in measured angle from the actual value. Most of the sensors are temperature independent, i.e. they perform equally within a wide range of temperature without any performance degradation. There is another variety of FBG based tilt sensor whose performance is dependent on the temperature and they are, therefore, used as temperature sensor as well. In this case, the temperature sensitivity is a key parameter for measuring the performance. Higher value of angle of inclination, sensitivity and temperature sensitivity indicates better performance of the sensor, whereas lower value of resolution and accuracy indicates better performance of the sensor. Several efforts have been made to increase the sensitivity of it as well as to make it temperature insensitive. Further research can be done in this direction to develop commercially viable tilt sensors.

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