

Review Article

Review of the Strain Modulation Methods Used in Fiber Bragg Grating Sensors

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Fiber Bragg grating (FBG) is inherently sensitive to temperature and strain. By modulating FBG's strain, various FBG sensors have been developed, such as sensors with enhanced or reduced temperature sensitivity, strain/displacement sensors, inclinometers, accelerometers, pressure meters, and magnetic field meters. This paper reviews the strain modulation methods used in these FBG sensors and categorizes them according to whether the strain of an FBG is changed evenly. Then, those even-strain-change methods are subcategorized into (1) attaching/embedding an FBG throughout to a base and (2) fixing the two ends of an FBG and (2.1) changing the distance between the two ends or (2.2) bending the FBG by applying a transverse force at the middle of the FBG. This review shows that the methods of "fixing the two ends" are prominent because of the advantages of large tunability and frequency modulation.

1. Introduction

FBG sensors have many inherent advantages over conventional electrical sensors, such as frequency modulation, immunity to electromagnetic interference, and nonconductivity [1–4]. These advantages are ideal for many applications such as structural health monitoring [5–8], medical applications [9–13], and seismic monitoring [14–17], especially for the applications where strong electromagnetic interference exists or nonconductivity is essential, such as nuclear reactors [18–20] and hydrogen tanks [21, 22]. FBG sensors have been successfully commercialized in many structural health monitoring applications, being an emerging substitute for electrical ones [23–27].

This review focuses on how the strain of an FBG is modulated in various FBG sensors, whereas comprehensive reviews on optical fiber sensors [28, 29] and fiber Bragg gratings [30] are available.

2. Working Principle of FBG

The working principle of FBG is shown in Figure 1. Bragg gratings are formed on the core of a single mode fiber by

changing its refractive index. When a broadband light goes through an FBG, the light at a certain wavelength will be reflected while all the other light will go through.

The resonant wavelength (the central wavelength of the reflected light) is [4]

$$\lambda = 2n_{\text{eff}}\Lambda, \quad (1)$$

where n_{eff} is the effective refractive index of the fiber core and Λ is the grating period.

When the strain ε changes [30],

$$\Delta\lambda = \lambda(1 - \rho)\Delta\varepsilon, \quad (2)$$

where ρ is the stress-optic coefficient. When temperature changes, the resonant wavelength will also change. Its inherent temperature sensitivity is about $10 \text{ pm}/^\circ\text{C}$.

The strain of an FBG has been modulated for varying its temperature sensitivity [31–40] and monitoring strain/displacement [41–49], inclination [50–56], acceleration [57–68], pressure [69–78], magnetic field [79–88], and rotation [89].

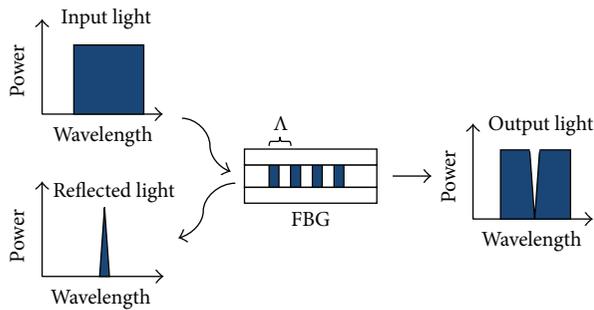


FIGURE 1: Working principle of an FBG.

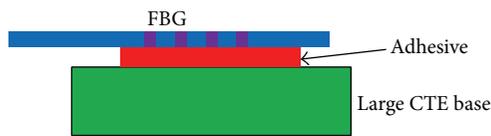


FIGURE 2: Large CTE base bonding method for temperature measurement [31].

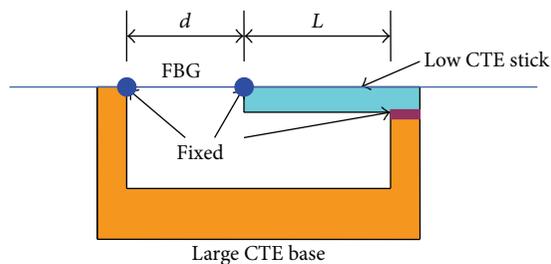


FIGURE 3: Bimetal method [33].

3. FBG Sensors

3.1. Varying Temperature Sensitivity

3.1.1. Large Coefficient of Thermal Expansion (CTE) Base Bonding Method. In order to increase its temperature sensitivity, an FBG was initially bonded to a base with a large Coefficient of Thermal Expansion (CTE), as shown in Figure 2 [31, 32]. When temperature changes, the strain of the FBG will change as much as that of the large CTE base. So the FBG becomes more sensitive to temperature.

3.1.2. Initial Bimetal Method. However, the sensitivity achieved in the above method is limited by the CTE of the base. Bimetal method was introduced to overcome this limitation, as shown in Figure 3 [33]. Assume that the length of the low CTE stick is L , and the distance between the fixed ends of the FBG is d . When temperature changes, the length-change of the large CTE base will be transferred to the FBG. To roughly estimate the strain change of the FBG, the temperature-induced, tiny length-change of the low CTE stick can be ignored. So the strain change of the FBG is $(1 + L/d)$ times that of the base. The strain change of the FBG is no longer solely decided by the CTE of the base, and ambient temperature sensitivity can be achieved.

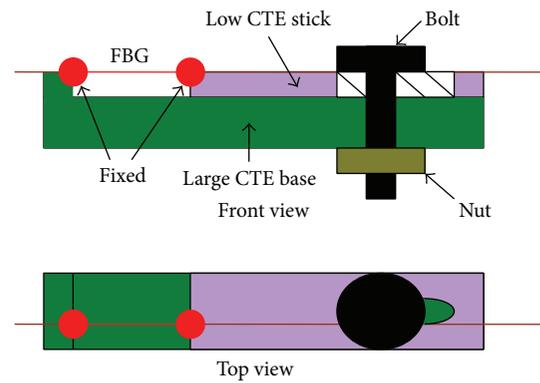


FIGURE 4: Bimetal method with adjustable measurement range [38].

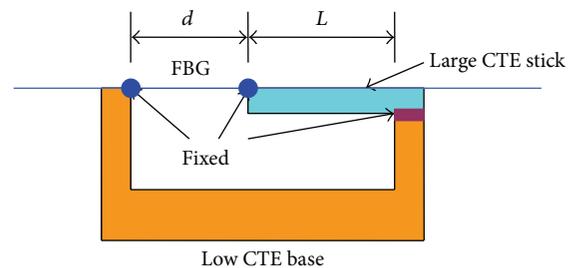


FIGURE 5: Bimetal method for low temperature monitoring [37].

3.1.3. Bimetal Method with Adjustable Measurement Range.

To make full use of the limited range of the strain change of an FBG to achieve the highest sensitivity possible for high temperature monitoring, the FBG in Figure 3 should be relaxed at room temperature. As temperature increases, it starts to be stretched at the low-limit of its measurement range and fully stretched at the up-limit [38]. Figure 4 shows the mechanics for achieving this function. The low CTE stick has a slot thereon. By adjusting the position of this stick, the FBG can be preredaxed for a certain length so that it starts to be stretched at the low-limit. With proper design of its sensitivity, the strain of an FBG can be fully used.

3.1.4. Bimetal Method for Low Temperature Monitoring.

However, only the large CTE base bonding method had been used for monitoring cryogenic temperature [34–36], because the initial bimetal method relaxes the FBG as temperature goes down rather than stretching it. A bimetal FBG sensor with negative temperature coefficient was demonstrated to achieve ambient sensitivity at low temperature by exchanging the positions of the bimetal, as shown in Figure 5 [37]. When temperature goes down, the FBG will be stretched, and ambient sensitivity can be achieved.

3.1.5. Bimetal Method for Temperature Compensation.

In order to eliminate the influence of temperature, the strain of an FBG can be changed to compensate its inherent temperature sensitivity. By using the abovementioned bimetal methods to make the temperature sensitivity zero [37],

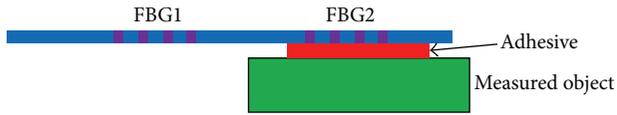


FIGURE 6: Simultaneous temperature and strain monitoring [44].

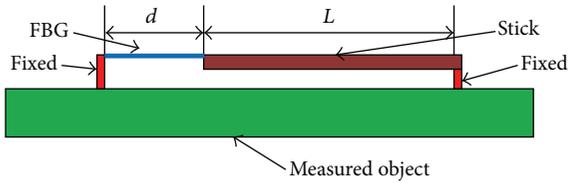


FIGURE 7: Strain monitoring by one FBG with automatic temperature compensation [48].

temperature-independent devices can be achieved [39, 40, 51].

3.2. Strain/Displacement Measurement. In strain/displacement measurement, as both strain and temperature are quasi-static in many applications, the strain has to be distinguished from the temperature.

3.2.1. Simultaneous Monitoring of Strain and Temperature. One extensively investigated method is to monitor both strain and temperature and then eliminate the influence of the temperature to determine the strain, which usually requires two FBGs [43–45]. Figure 6 shows one example. FBG2 is glued throughout on the measured object, whereas FBG1 is not. When the strain of the measured object changes, only FBG2 will respond; when temperature changes, both of them will respond. Based on the temperature response of FBG1, the temperature influence on FBG2 can be eliminated from its response, and the strain of the measured object can be obtained.

3.2.2. Strain Monitoring by One FBG with Automatic Temperature Compensation. Temperature can also be compensated by the temperature-induced length-change of a stick connected to the FBG, so that only one FBG is needed [48]. Figure 7 shows the principle. A tensioned FBG is fixed between a stick and the measured object. When only temperature changes, the temperature-induced length-change of the stick can keep the resonant wavelength unchanged. Therefore, the shift of the resonance wavelength of the FBG only represents the strain change of the measured object. When the measured strain changes, the stick does not change in length but the FBG does. So the strain change of the FBG is $(1 + L/d)$ times that of the measured object. Unlike the bimetal temperature-compensation method, the temperature compensation here is only based on the stick.

3.2.3. Strain Monitoring by Unevenly Changing the Strain of an FBG. By unevenly changing the strain of an FBG, the strain of a measured object can also be distinguished by the

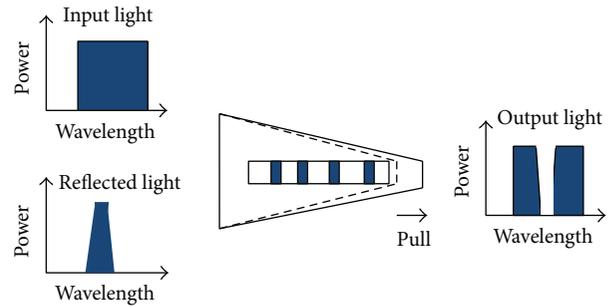


FIGURE 8: Strain monitoring by a chirped FBG [42].

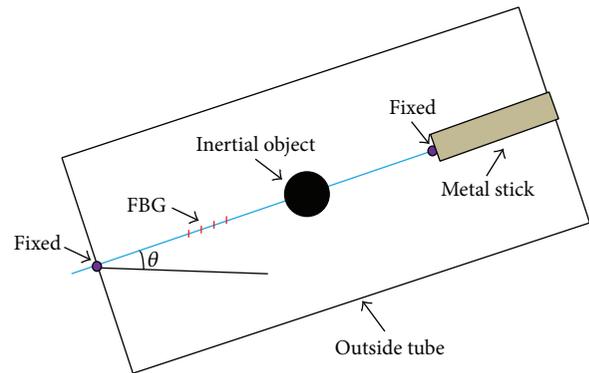


FIGURE 9: Uniaxial inclinometer [51].

power of the reflected light of an FBG, which is immune to temperature [42]. Figure 8 shows one example. The fiber is tapped, and its strain will change unevenly when it is pulled. The larger the uneven distribution, the wider the width of the reflected spectral response. When temperature changes, the width does not change, but its position shifts along the horizontal axis. However, this method loses the advantage of frequency modulation, as it is based on the power of the reflected spectrum rather than the resonant wavelength. FBG sensors based on this method are subject to noise produced by effects such as curves in the fiber.

3.3. FBG Inclinometers. FBG inclinometers have been developed by converting a tilted degree to the even or uneven strain change of an FBG. By connecting an inertial object with an FBG, the strain of FBG can be changed when the inclinometer is tilted.

3.3.1. Inclinometers Based on Even Strain Change. Figure 9 shows an FBG inclinometer by fixing an inertial object directly on an FBG [51]. If there is a tilted degree θ as shown, the inertial object will exert a force to extend the FBG. So the resonant wavelength of the FBG can represent the tilted degree. Temperature compensation can be achieved by the bimetal method [39, 40].

Figure 10 shows a planar biaxial inclinometer [52]. When there is an inclination, the resonant wavelength of the four FBGs will change. The difference between the resonant wavelengths of the two FBGs along one axis can be used to

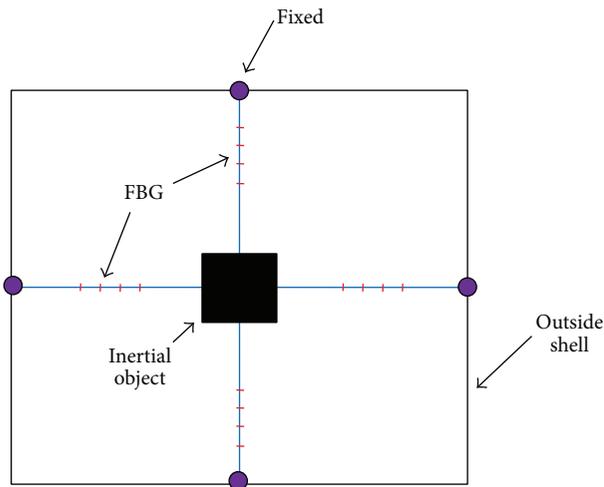


FIGURE 10: Top view of the planar biaxial inclinometer [52].

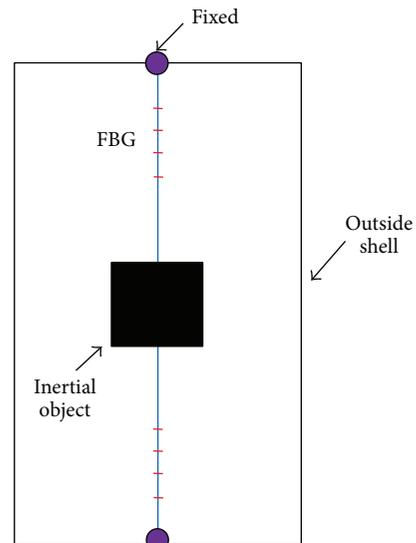


FIGURE 12: Uniaxial FBG accelerometer [66].

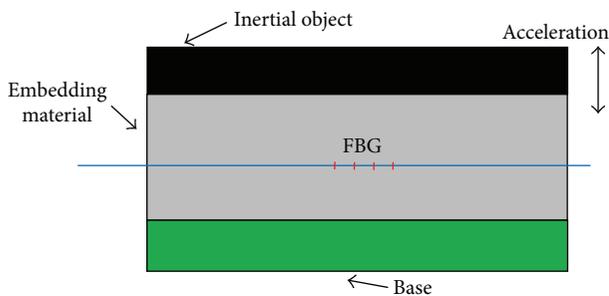


FIGURE 11: FBG accelerometer based on throughout attaching [65].

determine the inclination in that direction. The difference is immune to temperature, because temperature influences the two FBGs equally and the difference between them eliminates the influence.

3.3.2. Inclinometers Based on Uneven Strain Change. Since an inclinometer is based on the strain change of an FBG, the method of unevenly changing the strain of an FBG shown in Figure 8 can be adapted to monitor inclination, for example, the inclinometer in [50]. As discussed in Figure 8, this method relies on the reflected power rather than wavelength, losing the advantages of frequency modulation.

3.4. FBG Accelerometers. FBG accelerometers have been developed by using an inertial object to change the strain of an FBG according to the environmental acceleration.

3.4.1. FBG Accelerometers Based on Throughout Attaching. Figure 11 shows the first demonstration of FBG accelerometer [65]. In case of a vertical acceleration, the mass will move up and down. As a result, the strain of the FBG is changed periodically. Similar to the large CTE base bonding method used for high sensitivity temperature monitoring, this accelerometer cannot fully use the mass to exert large strain change of the FBG.

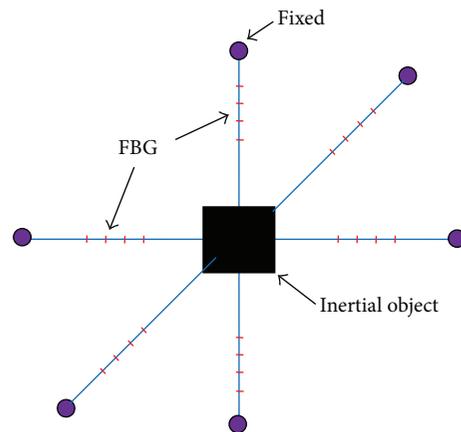


FIGURE 13: Triaxial FBG accelerometer [61].

3.4.2. FBG Accelerometers Based on Direct Forces. To achieve high sensitivity at low inertial mass, an FBG is fixed by its two ends, and an inertial mass is fixed at the middle of the FBG.

(1) FBG Accelerometers Using Axial Forces. Figure 12 shows a uniaxial FBG accelerometer using axial forces, which can transfer the movement of the inertial object into the displacement of the FBGs [62, 66]. When the inertial object moves up and down, the lengths and resonant wavelengths of the two FBGs will be changed. The difference between the resonant wavelengths represents the acceleration and is immune to temperature.

Figure 13 shows a triaxial FBG accelerometer, which uses 6 FBGs for three orthogonal directions [61]. The difference between the resonant wavelengths of the two FBGs along one axis represents the acceleration in that direction and is immune to temperature.

(2) *FBG Accelerometers Using Transverse Forces*. It has been demonstrated that when a transverse force applies to a lightly stretched string, it will induce a stronger axial force [67]. The optimum amplification condition is that the applying position is at the middle of the string, and the string is stretched as less as possible.

FBG accelerometers using transverse forces have two advantages: (1) requiring less FBGs for biaxial monitoring and (2) obtaining a higher sensitivity at the same inertial mass [58]. A biaxial FBG accelerometer was demonstrated by using a setup similar to that shown in Figure 12. The acceleration in the axial direction was distinguished by the difference of the resonant wavelengths of the two FBGs, while the acceleration in the transverse direction was distinguished by the average of the resonant wavelengths of the two FBGs. It was more sensitive to the transverse acceleration, as it was more sensitive to the transverse force.

3.5. FBG Pressure Sensors. When an FBG is exposed to a pressure, its strain will change. The relationship between the pressure applied and its induced strain change is [77]

$$\Delta\varepsilon = -\frac{P(1-2\nu)}{E}, \quad (3)$$

where P , ν , and E are the pressure applied, Poisson ratio, and Young's modulus of the fiber, respectively. However, the intrinsic pressure sensitivity is too low, only 3.14 pm/MPa [78]. The sensitivity was initially improved by embedding FBG into polymers (60 pm/MPa [72]).

The sensitivity is dramatically improved by fixing the two ends of an FBG and changing the axial distance between the ends (5.277 nm/MPa [74] and 33.876 nm/MPa [71]). Temperature influence can be compensated by using the bimetal method [70] or by using the difference between the resonant wavelengths of two FBGs along one axis [69].

3.6. FBG Magnetic Field Sensors. By using a magnetostrictive material to change the strain of an FBG according to the magnetic field, many FBG magnetic field sensors have been developed [79–88]. This method was early reported in [87], and a resolution of 2 mA has been reported [88]. Temperature can be compensated by using a reference FBG [80, 81]. To reduce the size, the cladding of the FBG was partially removed and then the magnetostrictive material was coated [79, 83, 85].

4. Categorization and Conclusion

Numerous FBG sensors have been developed by various methods. Figure 14 categorizes these methods based on how the strain of an FBG is changed. According to whether an FBG is stretched evenly or unevenly, it is divided into two categories.

In the “unevenly” category, the strain of an FBG is changed unevenly. What changes along with the environmental input is no longer the resonant wavelength but the power of the reflected light. FBG sensors based on these methods, for example, the method of strain monitoring by a chirped FBG, lose the intrinsic advantages of frequency modulation

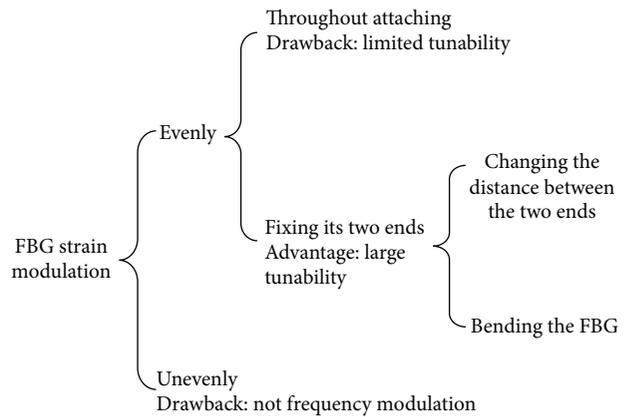


FIGURE 14: Categorization of FBG sensors according to how the strain of the FBG is changed.

and are subject to noise produced by effects such as curves in the fiber, although they are immune to temperature.

In the “evenly” category, there are two subcategories. The first subcategory, “throughout attaching,” includes the large CTE base bonding method, the simultaneous-temperature-and-strain-monitoring method, the FBG accelerometers based on throughout attaching, polymer embedded pressure sensor, and the FBG magnetic field sensors. The drawback of these methods is that the strain of an FBG can only be changed very limitedly and therefore the sensitivity is usually low.

The second subcategory is “fixing the two ends of an FBG,” which can be further subcategorized into (1) “changing the distance between the two ends” and (2) “bending the FBG.” “Changing the distance between the two ends” includes the bimetal methods, the automatic temperature-compensation method by using one FBG, the FBG inclinometers based on the even strain change, the FBG accelerometers based on direct axial forces, and the high sensitive FBG pressure sensors. These methods can change the strain of an FBG arbitrarily and effectively. “Bending the FBG” includes the FBG accelerometers using transverse forces [57–59, 67], which can be used to increase the sensitivity and reduce the number of FBGs required for biaxial monitoring. In conclusion, the methods in this subcategory, “fixing the two ends of an FBG,” are prominent because of the advantages of large tunability and frequency modulation.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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