KPU International Journal of Engineering & Technology
Volume 2, Issue2, Dec. 2022
e-ISSN:2790-0819, p-ISSN:2790-0800

Date Received: 2022-08-13
Date Accepted: 2022-12-24
Date Published: 2022-12-30

Combined Tapered Optical Fiber and FBG Sensor for Temperature and Strain Measurement

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Abstract

Fiber Bragg Grating (FBG) sensors have found more usages in the industry to diagnose the safety of mechanical structures due to their high sensitivity, non-exposure to the electromagnetic field, linearity, and lightness. A limitation of the application of FBG sensors is the inability to distinguish the effects of temperature and strain in the simultaneous measurement. For this purpose, we must somehow discriminate the effect of temperature on the strain. In this Article, by designing a tapered fiber-FBG composite sensor we have provided a solution for this problem. Studies performed on the designed composite sensor show that no sensitivity interference will occur in the sensor. In the composite sensor, a tapered fiber optic sensor with a temperature sensitivity of $-932.8\frac{pm}{℃}$ *and an FBG sensor with a temperature and strain sensitivity of* $9.89\frac{pm}{℃}$ *and* $0.92\frac{pm}{\mu\varepsilon}$*, respectively, are used.*

Keywords: Tapered fiber, Temperature sensor, FBG sensor, Strain, Structural health monitoring.

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1. Introduction

There are different types of optical fiber sensors, of which the thinned optical fiber sensor is one of the most important. In a standard optical fiber, the intensity of the wave field on the outer surface is almost zero. To make the optical fiber sensitive to the external environment, it is thinned. By tapering the optical fiber due to the reduction of the diameter of the optical fiber and the increase of the numerical aperture, the amount of penetration depth and the intensity of the attenuation wave field can be significantly increased [1,2].

This causes the output to show significant sensitivity to changes in the refractive index of the surrounding environment. Different parts of tapered optical fiber are shown in figure (1).

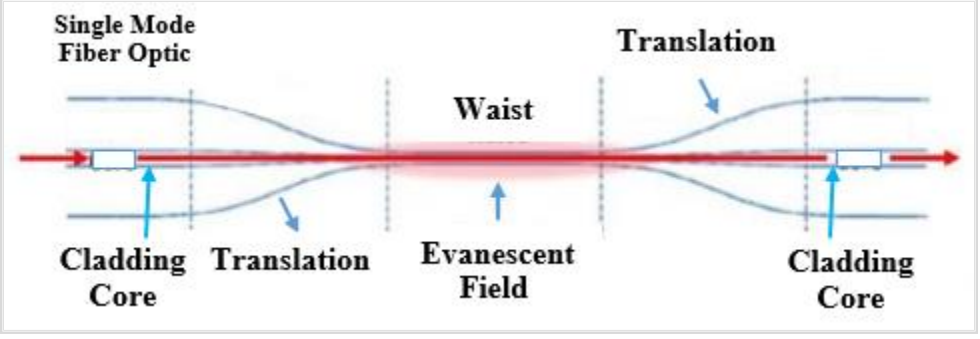
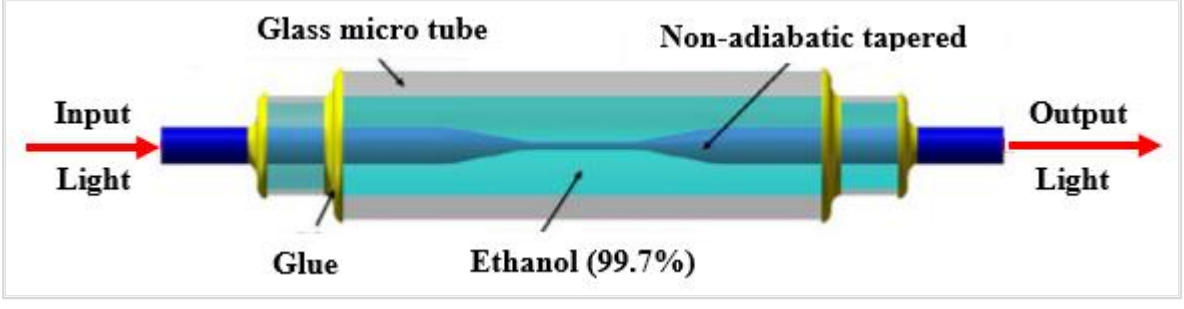


Figure (1). Schematic of tapered optical fiber and its different regions [3].

The performance of a tapered fiber optic-based temperature sensor relies on a sensitive laminated coating (absorber layer) on the surface of the optical fiber. In this situation, when the temperature of the surrounding environment changes, the physical and chemical properties of the tapered fiber change, and these changes change the properties of the light inside the fiber. Changes in the properties of the light beam inside the optical fiber include changes in the intensity, wavelength, or phase of the transmitted light; Therefore, by measuring the parameters of the transmitted light, the temperature value can be calculated (Figure (2)).



(Figure 2). Schematic diagram of temperature sensor based on thinned optical fiber [4].

Another type of fiber optic sensor is the Fiber Bragg Grating sensor. With the discovery of optical sensitivity in optical fibers, it became possible to make optical fiber Bragg Gratings. These gratings simply consist of periodic modulation of the refractive index inside the fiber optic core. Grid-like structures are very important in waveguide optics. Surface-enhanced lattice structures are used in flat waveguide optics for light refinement and coupling [5]. Optical fiber Bragg gratings have been considered a good sensor for measuring dynamic and static fields such as temperature and strain. One of the most important advantages of sensors made using optical fiber Bragg gratings is their wavelength-coding nature. This feature makes the Bragg grating sensors act as a self-reference, independent of the fluctuations of the light level and insensitive to changes in the light intensity of the source and losses caused by the connectors. Due to the low substitution loss and narrow bandwidth reflection wavelength, they can be easily wavelength multiplexed along a single-mode optical fiber [5]. Interferences of the refractive index lead to the reflection of light (propagated along the optical fiber) in a very small range of wavelengths, which is called the reflection wavelength of the Bragg grating or λ_B (Figure (3)). In addition to the periodicity of the Bragg grating, the reflected Bragg wavelength is dependent on temperature, strain, and other environmental factors, and by applying the smallest change in the said factors, we will have a shift in the reflected wavelength [6]. The intensified wavelength is reflected toward the source and the rest of the wavelengths pass through the part without change or attenuation. The reflection wavelength of an optical fiber Bragg grating is given as follows:

$$\lambda_B = 2n_{eff}\,\Lambda$$

Whereλ_B, n_{eff} and Λ is the Bragg wavelength (reflection wavelength), effective refractive index, and grating period, respectively.

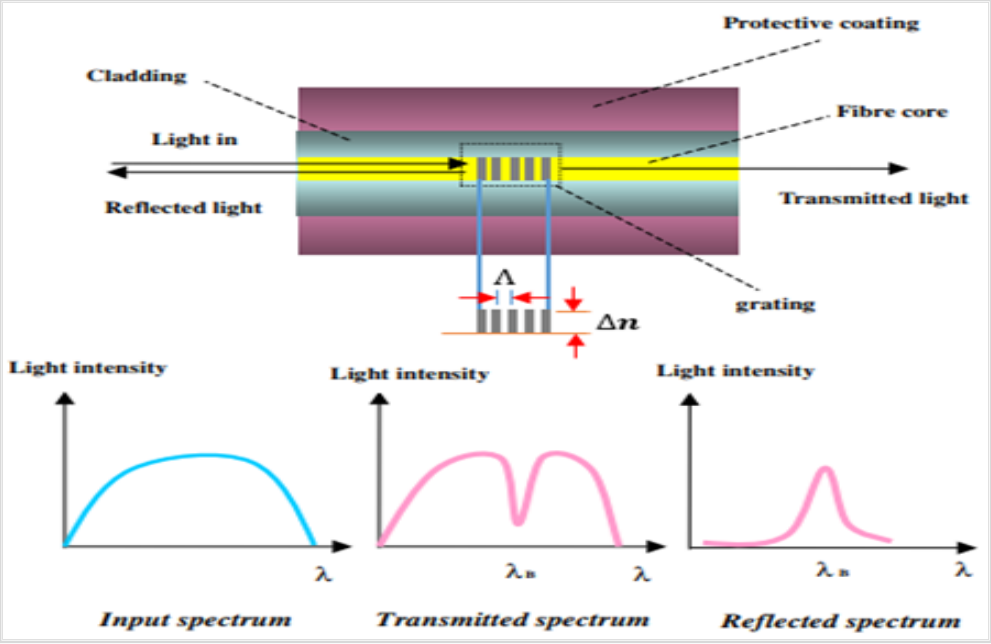


Figure (3). The general structure of optical fiber Bragg grating [7]

2. Research Methods

In this research, to Discrimination, the interference of temperature and strain in FBG sensors, a combined sensor design of tapered optical fiber (sensitive to temperature) and fiber optic Bragg grating sensor (sensitive to temperature and strain) was used to measure temperature and strain simultaneously and to separate We act on the effect of temperature and strain. By using the relationships between wavelength changes with strain and temperature, as well as measuring the amount of wavelength changed by each of the tapered optical fiber and the optical fiber Bragg grating, it is possible to determine the temperature and strain at the target point. To illustrate the proposed central idea, we use the experimental results of two types of sensors made by other groups. In reference [4], a temperature sensor based on tapered fiber has been tested. Temperature changes from 24°C to 38°C are considered with a step of 2°C. The wavelength range is from 1520 nm to 1620 nm, the waist diameter of the tapered area is about 8 micrometers and its length is about 20 mm. Also, the refractive index of 1.36 is considered. The value of the wavelength decreases almost linearly with increasing temperature, and the temperature sensitivity of -932.8 pm/°C has been obtained [4]. The diagram of the temperature relationship with wavelength changes for the temperature sensor based on non-adiabatic tapered optical fiber is given in figure (4).

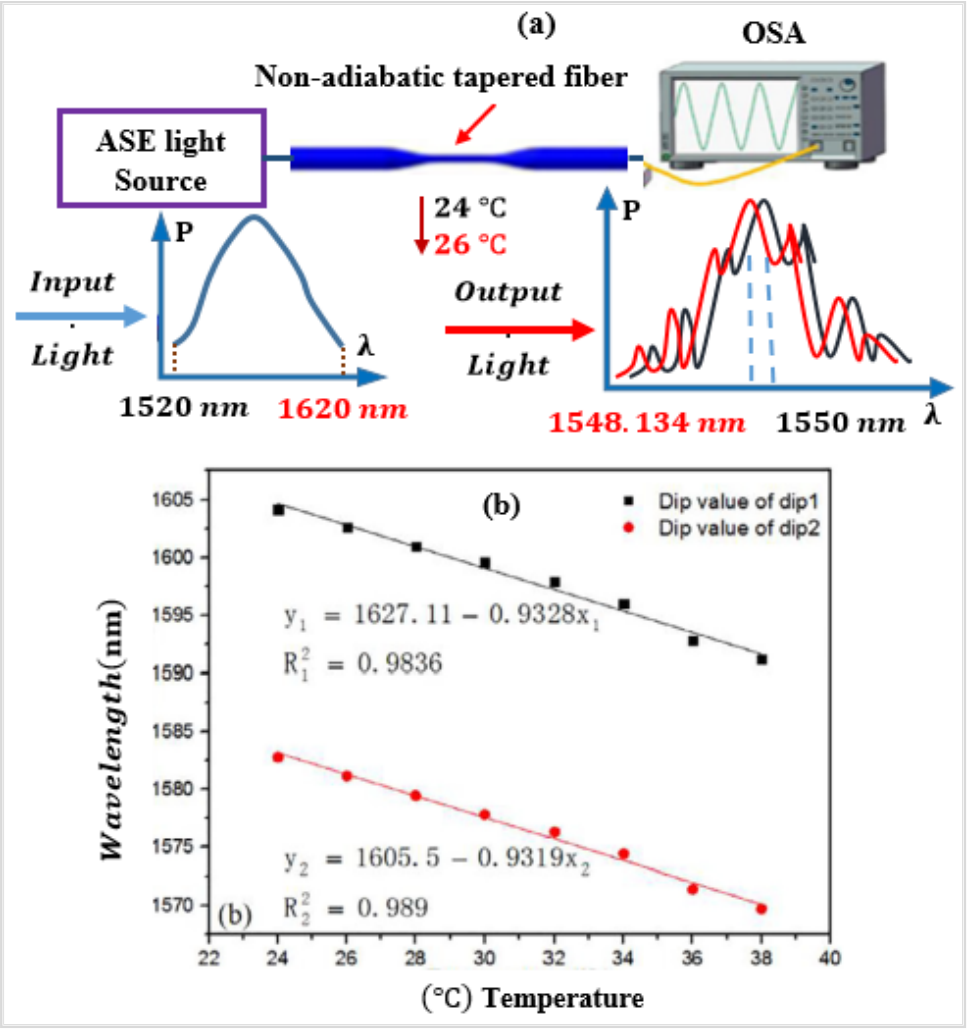


Figure (4). (a) Schematic diagram of tapered optical fiber-based temperature sensor arrangement which was designed by the author and (b) Wavelength change in the thinned optical fiber-based sensor due to temperature changes [4].

For the Bragg grating sensor, we use the laboratory results of reference [11]. The Bragg wavelength is 1530 nm, the effective refractive index is 1.444, and the temperature and strain sensitivity is $\frac{\Delta\lambda_B}{\Delta T} = 9.89\,{}^{pm}/_{°C}$ and $\frac{\Delta\lambda_B}{\Delta\varepsilon} = 0.92\,{}^{pm}/_{\mu\varepsilon}$ respectively, The temperature around the optical fiber Bragg grating was changed from 20°C to 80°C with a step of 20°C and the position of the reflection peak was measured. Wavelength changes in terms of temperature changes for the fiber Bragg grating are plotted in Figure (5).

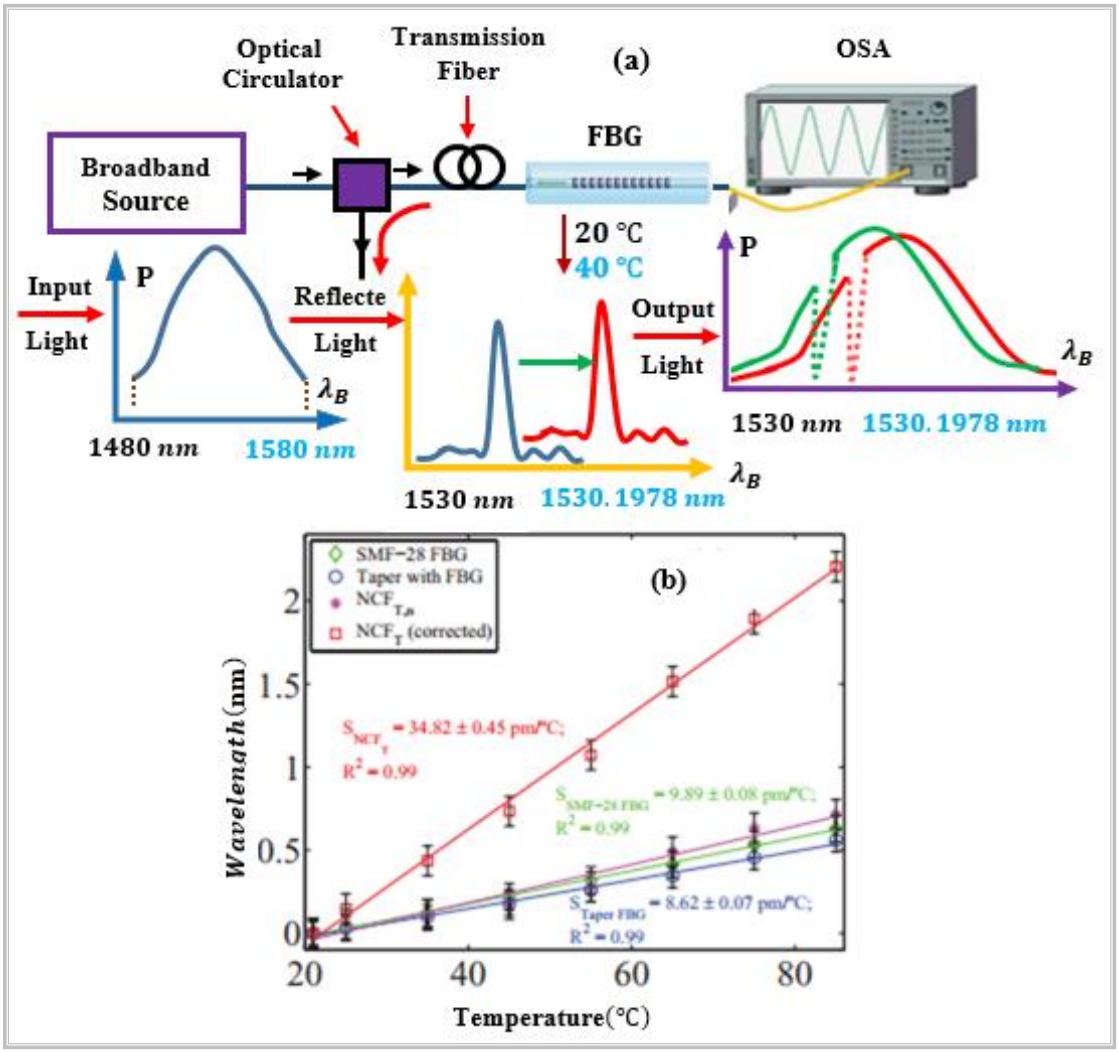
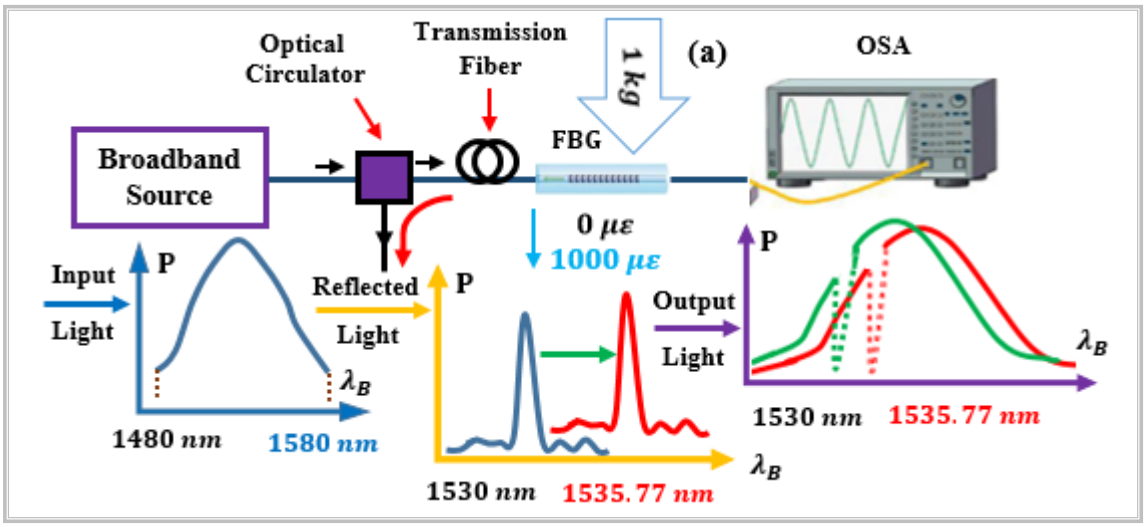


Figure (5). (a) Schematic diagram of Bragg grating sensor arrangement to measure temperature change which was designed by the author and (b) Change in wavelength at the peak of the reflection spectrum of FBG due to temperature changes [11].

To measure the strain, the amount of strain has been changed from zero to 1500($\mu\varepsilon$) microstrain with a step of 100($\mu\varepsilon$) microstrain [11]. Wavelength changes in terms of strain changes for optical fiber Bragg grating are plotted in Figure (6)



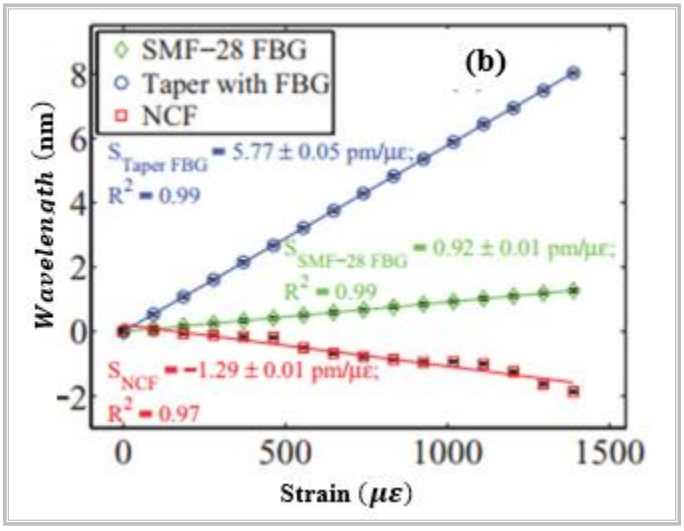


Figure (6). (a) Schematic diagram of Bragg grating sensor arrangement for strain change which was designed by the author and (b) Wavelength change in FBG due to strain change [11].

Now, we investigate the optical fiber Bragg grating sensor under the simultaneous influence of temperature and strain. This issue is shown schematically in Figure (7).

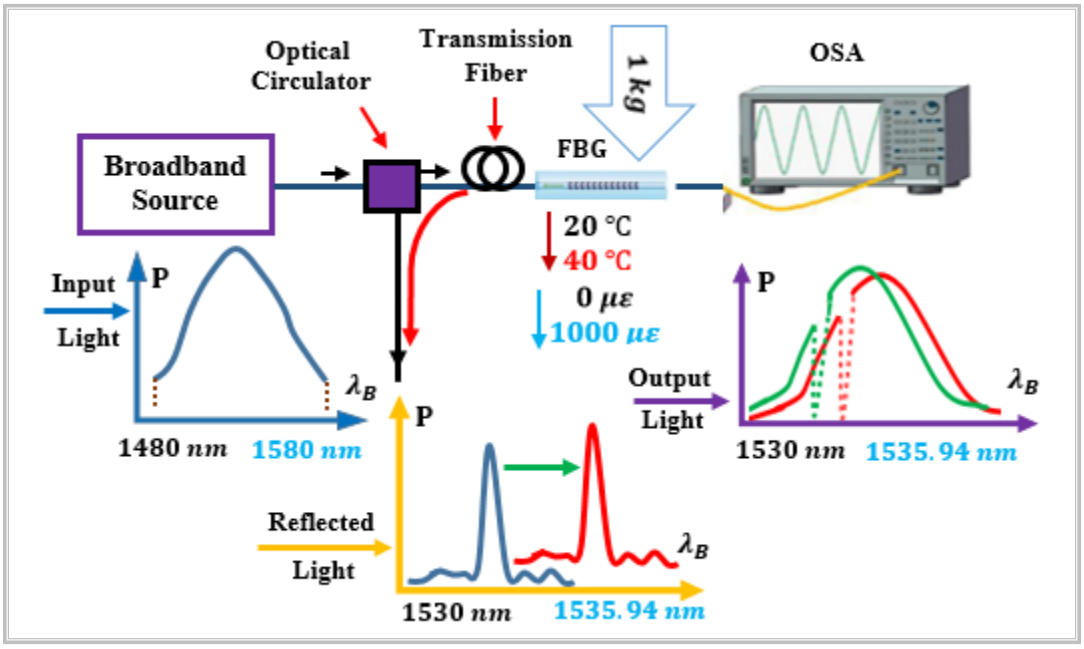


Figure (7). Schematic diagram of Bragg grating sensor arrangement due to a simultaneous change of temperature and strain designed by the author.

As it is clear in Figure (7), using the FBG sensor to measure temperature and strain simultaneously will cause sensitivity interference; and we cannot measure strain and temperature at the same time using this sensor. To eliminate the interference of temperature and strain, we investigate the design of a combined sensor of tapered optical fiber and FBG to measure temperature and strain simultaneously. The proposed sensor and the expected shift in the spectrum are schematically drawn in Figure (8).

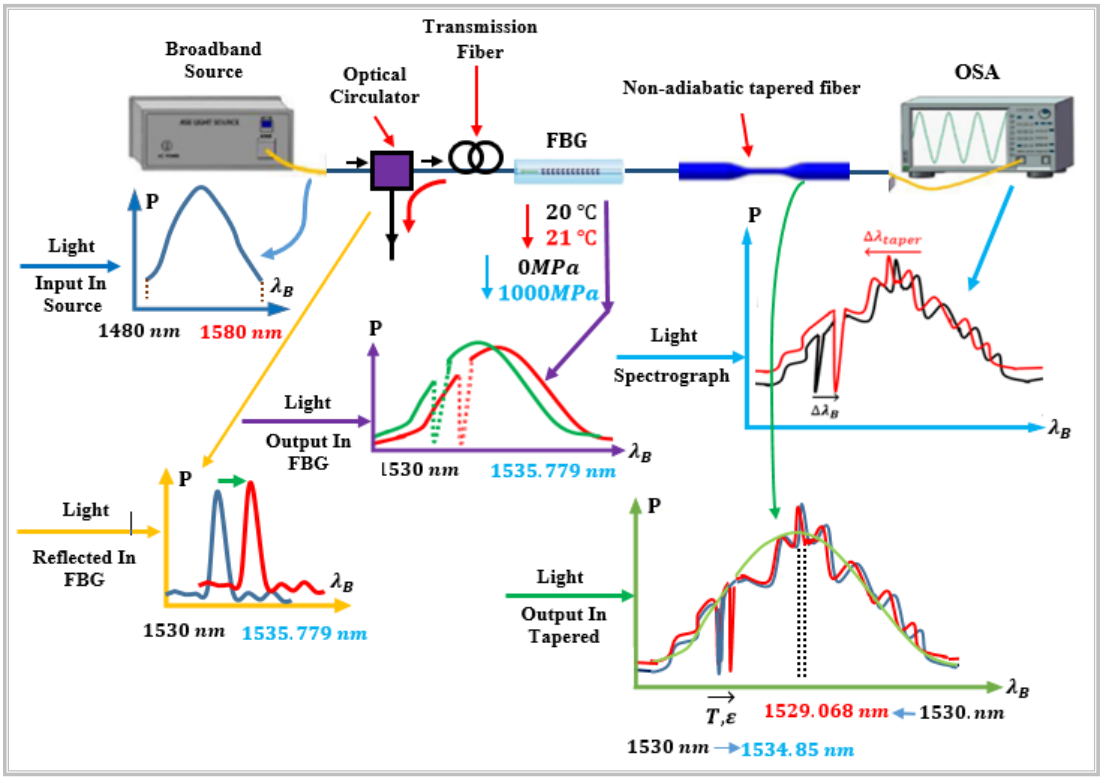


Figure (8). Schematic diagram of tapered optical fiber and FBG composite sensor arrangement due to temperature and strain changes designed by the author.

3. Results and Discussion

The temperature sensitivity of optical fiber Bragg gratings is calculated by the following equation [5]:

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \xi) \cdot \Delta T \qquad (1)$$

Also, the axial strain sensitivity of an optical fiber Bragg grating is obtained by the following equation [12]:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\varepsilon_z \qquad (2)$$

By combining equations (1) and (2), the overall sensitivity to temperature and strain is obtained.

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e) \cdot \varepsilon_z + (\alpha + \xi) \cdot \Delta T \qquad (3)$$

Equation (3) shows that the displacement of the Bragg grating is caused by two factors, strain, and temperature. To detect which factor the displacement is related to, a combined tapered optical fiber and FBG sensor can be used. The temperature-specific thinned fiber optic sensor and the FBG sensor examine both factors, which are obtained by comparing the temperature response of the thinned fiber sensors and the Bragg grating sensor and finally subtracting the result of both sensors from each other, the number of strain changes.

We rewrite equation (3) as follows:

$$\Delta\lambda_B = K_{\varepsilon B} \times \Delta\varepsilon + K_{TB} \times \Delta T \qquad (4)$$

Also, for the thinned fiber optic sensor which is sensitive to temperature, we have:

$$\Delta\lambda_{taper} = K_{T\,taper} \times \Delta T \qquad (5)$$

The values of $\Delta\lambda_B$ and $\Delta\lambda_{taper}$ can be seen in Figure (8), which can be determined in the laboratory. Now we perform an example of calculations for the proposed sensor. For example, let's suppose that in the laboratory we have measured the wavelength changes for the thinned optical fiber Δ and the Bragg wavelength changes separately and we want to determine the temperature and strain values. For example, let's suppose that in the laboratory we have measured the wavelength changes for the thinned optical fiber $\Delta\acute{\lambda}_{taper}$ and the Bragg wavelength changes $\Delta\acute{\lambda}_B$ separately and we want to determine the temperature and strain value. Assume that the values obtained for the wavelength change in the laboratory method for the thinned optical fiber sensor and FBG are $\Delta\acute{\lambda}_{taper} = -0.823\ nm$ and$\Delta\acute{\lambda}_B = 0.751\ nm$, respectively. Now we want to obtain the temperature and strain ($\Delta\acute{T}\ and\ \Delta\acute{\varepsilon}$) using these values.

$$\Delta\acute{T} = \frac{\Delta\acute{\lambda}_{taper}}{K_{T\,taper}} \implies \Delta\acute{T} = \frac{-0.823\ nm}{-0.9328^{nm}/_{\circ\mathrm{C}}} = 0.883\ ^{\circ}\mathrm{C} \qquad (6)$$

$$\Delta\acute{\varepsilon} = \frac{\Delta\acute{\lambda}_B - K_{TB}\times\Delta\acute{T}}{K_{\varepsilon B}} \implies$$

$$\Delta\acute{\varepsilon} = \frac{0.751\ nm - 0.00989^{nm}/_{\circ\mathrm{C}} \times 0.858\ ^{\circ}\mathrm{C}}{0.00092^{nm}/_{\mu\varepsilon}} = 807\ \mu\varepsilon$$

This shows that by using the adiabatic thinned optical fiber sensor and FBG in a combined form, the sensitivity interference will not be created in the said sensor, and strain and temperature can be measured simultaneously at any desired point. By using the relationship between wavelength changes with strain and temperature, as well as measuring the value of the changed wavelength by thinned optical fiber and optical fiber Bragg grating, it is possible to use the value of temperature and strain at any desired point. According to the measurements made in the references used in this article [4, 11], the

sensitivity for the said combined sensor for temperature and strain was obtained at 0.882 $^{pm}/_{\circ C}$ and 807 $^{pm}/_{\mu\varepsilon}$ respectively.

4. Conclusion

The limitation of using optical fiber Bragg grating sensors is that the response of the sensor to measure temperature and strain simultaneously can cause errors in strain measurement in different structures. For this purpose, we have to somehow separate the temperature effect from the strain effect, and various methods have been proposed for this task. In this paper, the design of thinned optical fiber hybrid sensor (sensitive to temperature) and an optical fiber Bragg grating sensor (sensitive to temperature and strain) was done to separate the effect of temperature and strain. Investigations conducted on the designed combined sensor showed that sensitivity interference will not occur in the said combined sensor. According to the sensors used as examples in this paper, the sensitivity for the combined sensor was obtained for temperature, 0.882 $^{pm}/_{\circ C}$ and for strain807 $^{pm}/_{\mu\varepsilon}$.

5. Acknowledgment:

The authors would like to thank Iran University of science and technology physics for providing research facilities.

6. Conflicts of Interest

All authors declare that they have no conflicts of interest to disclose.

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