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An Optimum Design Sapphire-Fiber Bragg Grating for High-Temperature Sensing

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Abstract: Fiber Bragg grating (FBG) sensors have limitations in measuring high and extreme temperatures because in general FBG sensors are made of silica fiber, which at high temperatures can interfere with the mechanical performance of the materials. In this paper, we propose an S-FBG (Sapphire Fiber Bragg Grating) sensor which is resistant to extreme environmental influences and high temperatures. By developing S-FBG to measure high temperatures, it is found that S-FBG has high sensitivity, every 1^{0}C change is obtained and the Bragg wavelength shifts as far as 30.24 nm, this result is greatly influenced by the thermo-optic coefficient, and the coefficient of expansion-thermal. The design also evaluates the Gaussian apodization profile to improve sensor accuracy in monitoring temperature.

Keywords: Sapphire FBG; High-Temperature; Sensor

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Introduction

High-temperature sensing is needed in many applications such as the oil and gas industry (da Silva et al., 2015; Zhong et al., 2021; Zhong et al., 2021), temperature monitoring in electrical transformers (Chai & Luo, 2019) and temperature sensing in nuclear reactors (Chai & Luo, 2019; Kumar et al., 2021; De Villiers et al., 2012). Monitoring of high temperatures and extreme environments (Yang et al., 2019) requires remote sensing without having to measure manually or by using a component that is resistant to interference from extreme conditions. Optical fiber technology, especially fiber Bragg grating (FBG) can be used as a sensor in extreme temperature sensing because FBG has a small size, is resistant to extreme conditions, is not susceptible to electromagnetic wave interference, and can be used as remote sensing (Li et al., 2021). When compared to electronic sensors or electro-mechanical sensors, FBGs offer much better benefits such as high sensitivity (Saktioto et al., 2021b) and multiplexing. As a temperature sensor, the FBG can shift the reflection wavelength every time the temperature changes. This occurs due to the coefficient of thermal expansion owned by the fiber (Saktioto et al., 2021a) (Ramadhan, and Toto, 2021), (Irawan et al., 2022)

Most of the FBGs sold in the market are made of silica, fiber with this material has also been proven to be able to be used as a sensor up to a temperature of 600 ^{0}C, limitations arise when FBG with silica is used in high-temperature measurements (Afroozeh, 2021; Ramadhan, 2020; Irawan et al., 2011; Irawan et al., 2010; Dedi Irawan et al., 2012)This weakness is a challenge by many researchers in the measurement of high temperatures. When high-temperature optical fiber exhibits viscoelastic properties at a temperature of more than 700 ^{0}C (Lindner et al., 2020)the fiber undergoes a deviation so that it cannot be used in temperature sensing.

In-vivo, in high-temperature sensing and extreme environments such as in measuring temperature in gas turbines and in fuel furnace endurance tests, sapphire-based FBG (S-FBG) can be used (Elsmann, 2013), it was reported that S -FBG can be an alternative in high-temperature measurement because S-FBG remains optically and mechanically stable at high

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temperatures(Wang et al., 2021). Habisreuther et al reported that S-FBG can measure temperatures in induction furnaces up to 1500 ^{0}C and obtained a resolution of ±2K at 20 Hz monitoring (Habisreuther et al., 2015), and also found that S-FBG can measure temperatures up to 1900 ^{0}C, Elsman et al reported that S-FBG which had a core mixed with 50% mol of aluminum found that S-FBG could measure temperatures up to 950 ^{0}C for 24 hours (Elsmann et al., 2014).

The diameter size of the core and cladding S-FBG determines in terms of sensitivity, the diameter size will result in more than one transmission mode, and each mode will provide different characteristics and will affect the sensitivity felt by the S-FBG. Guo et al used S-FBG in high-temperature measurements using S-FBG measuring 10 µm for the core and 125 µm for the cladding, in measuring temperatures up to 100 ^{0}C, the sensitivity of S-FBG in measuring temperature and strain was 15.64 pm/^{0}C and 15.64 pm/^{0}C, respectively. 1.33 pm/^{0}C (Guo et al., 2021) this result is still far from the results obtained by Usaireuther et al, namely 30 pm/^{0}C and 1.4 pm/^{0}C. from the results of the fabrication carried out by the previous research, it shows that the performance of S-FBG is not yet maximum and can be improved.

Therefore, in this paper, we propose an S-FBG design that has optimum performance in terms of sensitivity to temperature and strain, narrow and highly accurate FWHM in measuring high temperature and extreme environments, we also investigate the effect of apodization in our design.

Method

The method used in this research is a numerical simulation using Couple mode theory (CMT) with the help of Optigrating software. The proposed sensing scheme is shown in Figure 1.

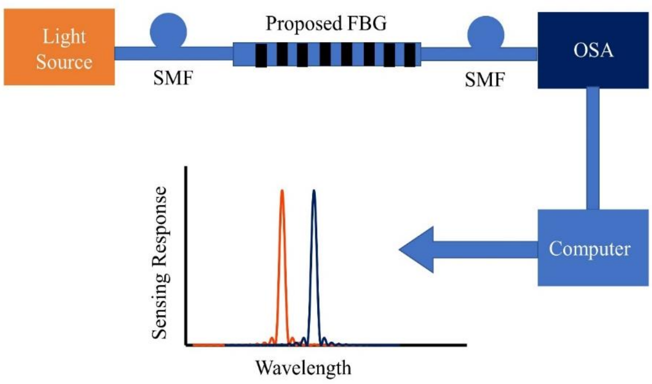

Figure 1. S-FBG sensor sensing scheme

The parameters of the design of S-FBG components can be seen in Table 1, these parameters refer to previous studies.

Table 1. Parameters S-FBG sensor

Parameters	Values
Refractive index core	1.7 (Elsmann, 2013)(Sahm, 1982)
Refractive index cladding	1
Thermal expansion	7.15 x 10^{-6}/^{0}C (Elsmann, 2013) (Sahm, 1982)
Thermo-optic coefficient	12 x 10^{-6}/^{0}C (Sahm, 1982) (Elsmann, 2013)
Core diameters	8
Cladding diameters	125
Period	
Grating length	80
Grating shape	sine

The parameters of the S-FBG components are as shown in Table 1, some parameters are set based on previous studies and evaluated for their performance by combining the apodization profiles. The design of the S-FBG component provides recommendations for fabricating components and is analyzed to obtain the S-FBG component with optimum performance in measuring high temperatures.

Result and Discussion

Electromagnetic waves propagate on the sapphire material to further transmit the signal and reflect the signal due to the presence of the S-FBG lattice. After simulation using Optigrating, we get a shift in the S-FBG reflection wavelength as shown in Figure 2, it is found that the Bragg wavelength has a very linear gradient. to high-temperature changes in this design. Simulations are carried out at a temperature range of 1500 ^{0}C to 1600 ^{0}C, this temperature range is usually very much needed by FBG with materials that are resistant and do not interfere with the mechanical properties of the measurement.

At a temperature of 1500 ^{0}C, the peak of the Bragg wavelength was at 1594.31 nm, there was a large shift. When the reference temperature was at 25 ^{0}C, it was 1550 nm, when the temperature was increased by 20 ^{0}C, the Bragg wavelength was found to be at 1594.92 nm, an increase of 0.6048 nm occurred. , then the temperature is increased by 20 ^{0}C, there is also an increase in the peak of the Bragg wavelength, so that from the simulation results it is obtained that the sensitivity of S-FBG to high temperatures is 30.24 nm/^{0}C and it is found that for every 1 ^{0}C change in temperature, the Bragg wavelength will experience a shift. of 30.24 nm, this result is certainly better when compared to FBG with silica material in normal temperature measurements, it is known that FBG with silica material has a temperature sensitivity of 13.4 nm/^{0}C. This means that when there is a change of 1

^{0}C in temperature, the Bragg wavelength only shifts as far as 13.4 nm, the sensitive FBG will give a large shift for very small temperature changes in the measurement. The Bragg wavelength is theoretically affected by the effective refractive index and lattice period of the FBG as in equation 1.

$$\lambda_{Bragg} = 2n_{eff}\Lambda \quad (1)$$

λ_{Bragg} is the Bragg wavelength, n_{eff} effective refractive index and Λ is the lattice period. Meanwhile, the shifting Bragg wavelength is strongly influenced by the coefficient of thermal expansion and the optical thermos coefficient, this supports what is stated in equation 2.

$$\Delta\lambda_{Bragg} = [\varphi + \vartheta]\Delta T \quad (2)$$

Where φ is the coefficient of thermal expansion, the value of the coefficient of thermal expansion and the thermo-optic coefficient ϑ For Sapphire material, it can be seen in Table 1. The coefficient of thermal expansion and thermos-optic coefficient greatly affects the shift in the Bragg wavelength resulting from S-FBG. Likewise, the value of the coefficient of thermal expansion and the thermos-optic coefficient of sapphire material is greater than that of silica material. Actually the S-FBG Bragg wavelength is not only sensitive to the influence of temperature, but also very sensitive to changes in strain, and the cross effect of the magnitude can also be separated in many ways, several studies have reported the cross effect of strain and temperature, by making the FBG pair with one one component is isolated from one of the quantities. And after that it will be used as a reference, but in this study, the effect of strain from the Poisson ratio value is considered constant for the designed component.

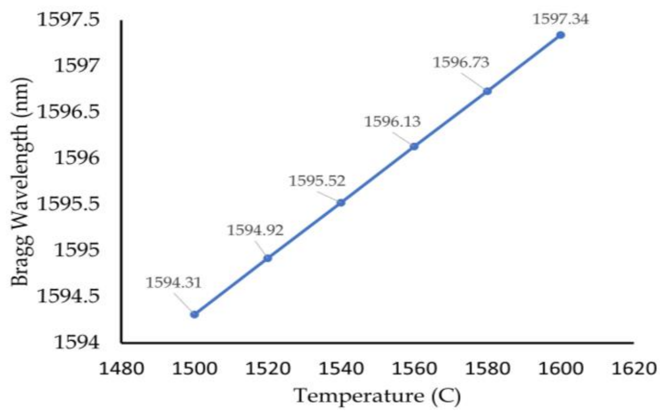

Figure 2. S-FBG Sensitivity to High Temperature

Furthermore, from the results of the characterization carried out the reflection and transmission wavelengths generated from the S-FBG component can be seen in Figure 3 and Figure 4, respectively, the magnitude of the transmission and reflection spectrum values must be in accordance with the law of conservation of energy, when the laser enters the S-FBG and passing through the lattice with periodic changes in refractive index, the input laser signal will be divided into 2 types, the first signal will be forwarded or called a transmission signal, the shift in the transmission signal that occurs in the characterization of the components can be seen in Figure 4, the power generated for each different temperature remains the same but there is a shift in the reflection peak, in this design the effect of apodization is also evaluated, the effect of apodization on the theoretical S-FBG spectrum signal can be seen in equation (3).

As previously reported, apodization can improve FBG performance and can also provide accuracy in temperature and strain measurements on FBGs. The second signal is the reflection signal or also known as the Bragg wavelength. The Bragg wavelength is the reflected signal. When the laser begins to enter the grating, the lattice structure in this performance evaluation is as shown in Figure 1. The selected grating is linear and the angle formed by the grating with respect to the horizontal axis is 0 degrees. For the apodization profile carried out in this study, Gaussian apodization and no chirp apodization were carried out.

$$n_{eff}(z) = n_0 + f(z)\Delta n_{ac} v \cos\left(\left(\frac{2\pi}{\Lambda}\right) + \theta(z)\right) \quad (3)$$

Where z represents position, n_0 denotes the initial refractive index, Λ is grating period, Δn_{ac} denotes the refractive index modulation amplitude, $f(z)$ connotes the apodization function, and $\theta(z) = 2\pi Cz^2/\Lambda$ is a chirp function where, C is the chirp parameter, and v represents peripheral visibility.

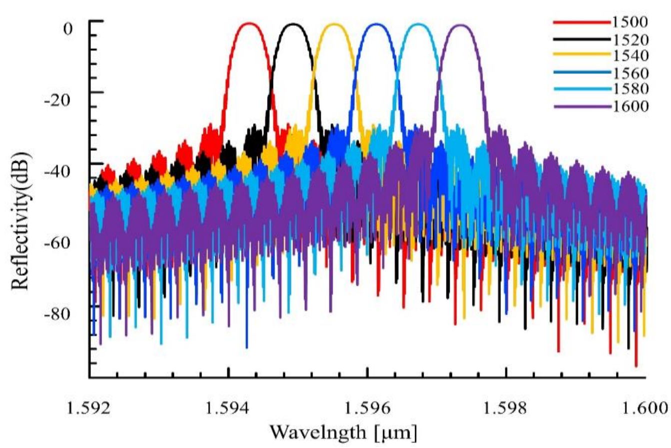

Figure 3. S-FBG Reflection Spectrum Shift in High Temperature

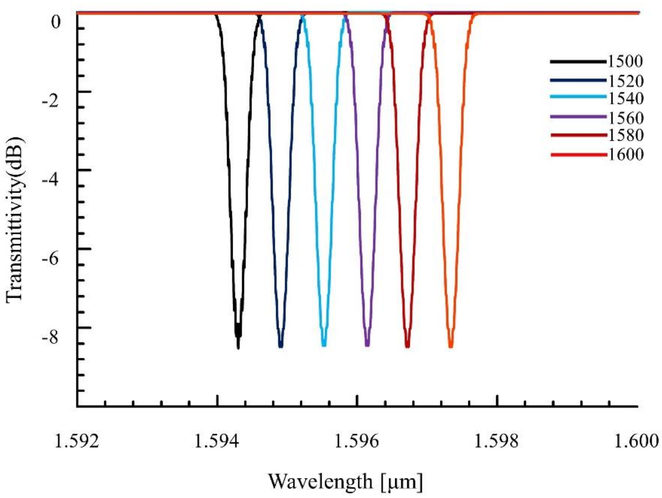

Figure 4. S-FBG Transmission Spectrum Shift in High Temperature

Furthermore, the effect of the apodization profile is evaluated in this design and the results of the reflection spectrum are obtained as shown in Figure 5. The apodization profiles evaluated in this design are the Gaussian and Uniform apodization profiles, to show the difference in accuracy of the two apodization profiles. And also refers to research conducted previously, but with different FBG materials.

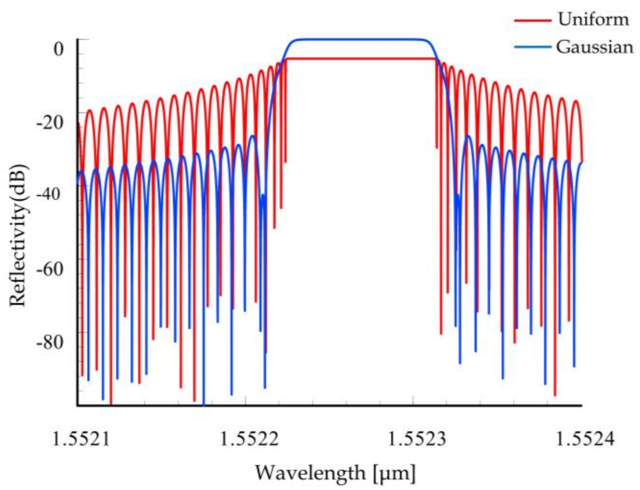

Figure 5. Evaluation of apodization profile on S-FBG

As Figure 5 shows the effect of the gaussian apodization profile on the reflection spectrum, the gaussian apodization profile has a sidelobe (SL) difference with a wide main-lobe (ML) compared to a uniform apodization profile, the sidelobe and main-lobe differences provide accurate information on the S-FBG sensor. It is known that the sidelobe and ML differences of the Gaussian apodization profile of 0.0643 nm are greater than the uniform apodization profile which only has SL and ML differences of 0.0594. The big difference between SL and ML is that they provide accurate sensor information in measuring physical quantities. Theoretically the apodization profile will affect the effective refractive index on the S-FBG as in equation 3. While the gaussian apodization profile mathematically as in equation 4.

$$A(z) = \exp\left(-\ln 2\left(\frac{2\left(z-\frac{L}{2}\right)}{0.5L}\right)^2\right) \quad (4)$$

Where $0 \le z \le L$

Meanwhile, the uniform apodization profile can be mathematically explained by equation 5.

$$A(z) = 1 \quad (5)$$

Where $0 \le z \le L$

From the above equation it is shown that the apodization profile can provide accuracy in the resulting reflection spectrum.

Conclusion

From the results of the research reported in this paper, we found that S-FBG can be used as an alternative in measuring high and extreme temperatures, this refers to the value of the optical thermos coefficient and thermal expansion coefficient of Sapphire material that can withstand high temperatures well, from the design It was found that the sensitivity of S-FBG in measuring temperature in the range of 1500 C to 1600 C was 30.24 nm/C, which proved to be more sensitive than silica.

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68

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